# DRAFT – BNL Proposal to Conduct Detector R&D - DRAFT
# for a Future U.S. Neutrino Physics Program
# Brookhaven National Laboratory and University Partners
# October XX, 2005

**[Version: October 31, 2005]**

## Executive Summary


This is a proposal submitted by Brookhaven National Laboratory (BNL), together with university partners having compatible research goals, to the U.S. Department of Energy (DOE), Office of High Energy Physics (OHEP), to conduct ***Detector R&D*** focused on the improvement of detector technologies and capabilities to support a more effective pursuit of future programs of neutrino research, especially in the ***neutrino oscillations*** sector where the scope of a definitive physics program can already be foreseen. Our proposals emphasize the R&D needed to optimize the design of a megaton-scale detector to be jointly used by the next-generation long baseline neutrino oscillations and proton decay experiments. These experiments are planned to share a large, combined-use detector located in the future Deep Underground Science and Engineering Laboratory (DUSEL) now being developed by the National Science Foundation. The combined-use detector concept was noted as a high priority program objective in the "Theme 2: Dark Matter, Neutrinos, and Proton Decay" section of the February 2004 Office of Science and Technology Policy (OSTP) report, "The Physics of the Universe"[1]. The Detector R&D work proposed here will contribute centrally to the effectiveness of this important future national research direction.

Although we identify the large DUSEL detector as a key focus of this proposal, we also propose R&D tasks for intermediate-term neutrino projects. Specifically, we note that better liquid scintillators could greatly benefit near-term reactor and short-baseline neutrino experiments as well as potentially contribute to a very large scintillator-based DUSEL detector. We outline a topical detector R&D program that is structured to evolve over a three-year period, indicating technical goals, requested OHEP support levels and staffing to meet the R&D objectives. The individual R&D tasks are described in the main text.

The proposed R&D work is submitted by a collaboration of Laboratory and university research scientists who plan to pursue complementary goals for the improvement of detector techniques and technologies that can advance the capability of the next-generation detectors for neutrino physics and proton decay searches. Our 1st priority is the development of integrated event simulation and pattern recognition software to optimize the signal to background ratio in large neutrino detectors. We will use the new software to critically compare the capabilities of water Cerenkov, liquid Argon and liquid scintillation detectors. Our 2nd priority is the development of improved photo-sensors for the water Cerenkov and liquid scintillator detectors, possibly combining imaging optics with pixellated photo-sensors. Our 3rd priority is the detailed understanding of these same detector technologies for their practical use in large or intermediate size neutrino detectors.

We supply here, a Table of proposed Detector R&D projects in the collaboration's priority order.


**Table of BNL/University Neutrino Detector R&D Topics**

| Project Name | R&D Priority | **FY 2006 (FY06 $K)** | **FY 2007 (FY06 $K)** | **FY 2008 (FY06 $K)** | **Sum (FY06 $K)** |
|---|---|---|---|---|---|
| Detector Simulation/Reconstruction Software | 1 | 364 | 154 | 100 | 618 |
| Photo-sensor R&D | 2 | 574 | 524 | 402 | 1500 |
| Liquid Scintillator Detector R&D | 3 | 759 | 779 | 960 | 2498 |
| Liquid Argon Large Detector R&D | 3 | 200 | 200 | 200 | 600 |

[1] "The Physics of the Universe, a Strategic Plan for Federal Research at the Intersection of Physics and Astronomy ", National Science and Technology Council Committee on Science, February 2004, http://www.ostp.gov/html/physicsoftheuniverse2.pdf ; also, "FY 2007 Administration Research and Development Budget Priorities", J.H. Marburger, III and J.B. Bolten, Executive Office of the President Memorandum, July 8, 2005, http://www.ostp.gov/html/budget/2007/ostp_omb_guidancememo_FY07.pdf .

**Main Proposal**

## <u>Introduction</u>:

We urge that a *large underground detector* with an active mass greater than 100kT become a key *shared physics research facility* for the future U.S. particle, nuclear and astrophysics research programs. A recent U.S. Government policy document, "The Physics of the Universe"[1], considers the science and technology that would be provided by such a detector and concludes that it has high scientific value and is also judged to be "Ready for Immediate Investment and Direction Known" (Page 5). To bring this policy position to practical application, a near-term program of research and development is needed to decide on the appropriate detector technologies, perform engineering design studies related to credible sites for such a detector, and determine the cost and schedule for such a detector. The recently announced DOE-OHEP Neutrino Physics R&D initiative is an appropriate venue for pursuing the required detector R&D objectives. The National Science Foundation is currently carrying out a process to identify an optimum site for this program under its "Deep Underground Science and Engineering Laboratory" (DUSEL) initiative. The candidate DUSEL sites have recently been reduced to two by the NSF[2]; these sites are the Henderson (Colorado) and Homestake (South Dakota) mines.

A sensitive large detector with appropriate technical capabilities will address questions of fundamental importance, such as nucleon decay and matter-antimatter asymmetry amongst neutrinos. The detector will also serve as a facility for continuously observing natural sources of neutrinos and cosmic rays. All these tasks are active *simultaneously*. We briefly summarize these physics research topics below.

The large detector must have mass in excess of 100kT to have significantly greater statistical reach to search for nucleon decay and to collect enough neutrino interaction events from accelerator-based neutrino beams with very long baselines to measure oscillation parameters with greater precision. The detector needs to have a low energy threshold (<5MeV) and good energy resolution to detect supernovae and solar neutrinos. It should have good pattern recognition, timing and particle identification capability to distinguish electrons from muons and pions. To exploit the full scientific potential of such a detector, it will have to be located deep underground to shield it from cosmic ray background. Currently, only three technologies, water Cerenkov, liquid Argon time-projection, and liquid scintillator, meet most of these requirements and lead to affordable designs.

The advantage of a water Cerenkov detector is that it is a proven technology that has been perfected over several decades. Liquid Argon time projection chambers potentially offer very detailed measurements of particle physics events with superb resolution and particle identification. A new liquid scintillation detector could have very low energy threshold and coincidence capability to observe rare events. Water Cerenkov detectors are in operation in Japan (Super Kamiokande with a total mass of ~50 kT) and in Canada (the Sudbury Neutrino Observatory, SNO, with 1 kT of $D_2O$ and 5 kT of $H_2O$). The ICARUS liquid Argon experiment is in the process of installing 600 tons of detector in the Gran Sasso Laboratory in Italy. The largest liquid scintillator detector in operation today is Kamland in Japan with 1.2 kT of liquid scintillator in its fiducial volume.

A program of R&D to further develop these technologies and to make a well considered choice among them is especially appropriate at this time because of the intense new interest in the physics of neutrinos ("The Neutrino Matrix,"[3] and the National Science Foundation's DUSEL process noted above. A unique opportunity for science could come to fruition in the US by combining a new deep laboratory, a large detector and intense neutrino beams from existing accelerators at national laboratories.

[2] *DUSEL announcement, http://www.nsf.gov/news/news_summ.jsp?cntn_id=104313&org=MPS&from=news*
[3] *"Neutrinos and Beyond – New Windows on Nature", National Research Council Study, National Academies Press, 2003.*

**Principal Investigators:**

The Detector-related Neutrino R&D Tasks, described in some detail in the sections below, will be managed by the following Principle Investigators (PIs). All the proposed work will be performed by BNL and collaborating university personnel as detailed in the task writeups.

| R&D Task | Principal Investigator(s) |
|---|---|
| Task 1 – Neutrino Source & Physics Reach Software | M. Diwan, BNL Physics Department |
| Task 2 – Water Cerenkov Detector Simulation/Reconstruction | B. Viren, BNL Physics Department |
| Task 3 – Background and Analysis Package for WC Detector | C. Yanagisawa, SBU Department of Physics |
| Task 4 – Implementation of VLBNO Experiment in GLoBES | M. Dierckxsens, BNL Physics Department |
| Task 5 – Photo-Sensor Development for Large Detectors | M. Bishai, BNL Physics Department |
| Task 6 – Gd-Loaded Liquid Scintillator for Reactor Exps. | R. Hahn, BNL Chemistry Department |
| Task 7 – Fine-Grained Liquid Scin. Detector Development | R. Tayloe, Indiana Univ. Phys. Dept. |
| Task 8 – Application of Liquid Scintillator to Large Detectors | R.S. Raghavan, VirginiaTech. Univ. Phys. Dept. |
| Task 9 – Application of Liquid Argon to Large Detectors | B. Fleming, Yale University, Physics Dept. |

**1.0 Scientific Scope:**

A large, 500 kT water Cerenkov detector can simultaneously address three broad physics research topics:

1) neutrino oscillations with a very long baseline and accelerator-produced super neutrino beam;
2) an improved search for nucleon decay;
3) detection and study of neutrinos from natural sources such as the Sun, Earth's atmosphere, past or current supernova explosions plus, as yet unsuspected new sources of neutrinos.

Arguments have also been advanced that a less massive detector in the 100 KT range, with full event reconstruction, such as a liquid argon detector, could successfully compete with water Cerenkov as the most cost efficient detector for the physics goals identified here. Some ideas have also been developed that could allow new, advanced concepts for liquid scintillator-based, large detectors to contribute to one or more of the physics topics. In the paragraphs following, our physics topics are briefly elaborated to motivate pursuit of R&D to develop detectors able to effectively pursue the goal of unveiling these important future discoveries.

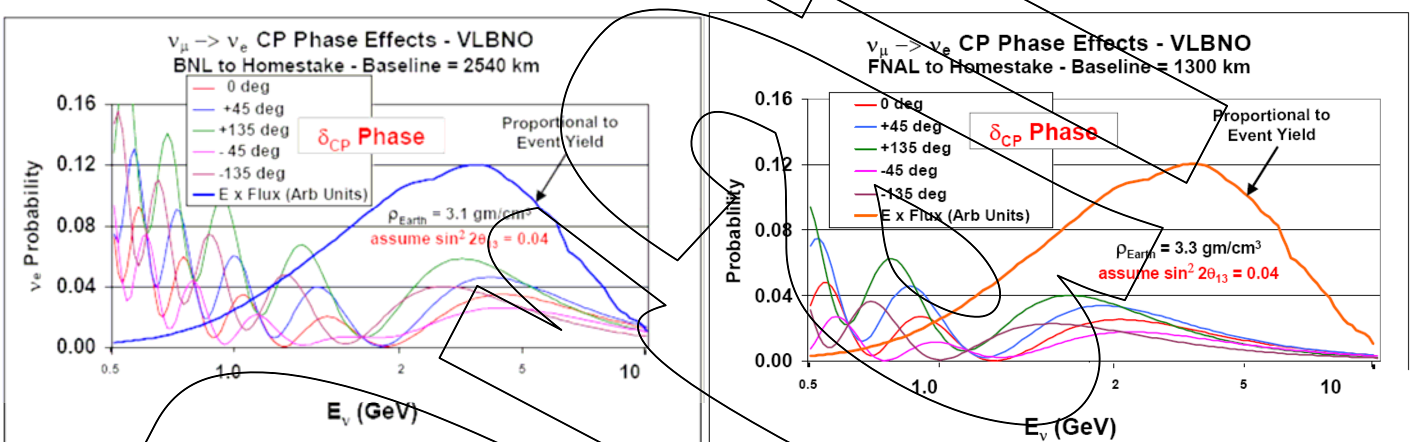
Physics Topic 1 – Neutrino Measurements Using Accelerator Produced Beams

In references[4,5,6], as well as additional references contained therein, it has been argued that an intense, accelerator-generated, broad-band muon neutrino beam, coupled with a large experimental detector located more than 1000 km away from the beam source, could be used to perform precision measurements of neutrino oscillation properties such as the mass differences, the mass hierarchy, the mixing parameters, and CP-violation in the neutrino sector. Using currently known values for the neutrino mass differences and mixing parameters[7], several rules of thumb have been formulated to characterize such an experiment:

1) For precise measurements of $\Delta m_{32}^2$ and $\sin^2 2\theta_{23}$, it is desirable to observe a pattern of *multiple nodes in the energy spectrum* of muon neutrino disappearance. Since the cross section, Fermi motion and nuclear effects limit the resolution of muon neutrino interactions below ~1 GeV, a wide-band muon neutrino beam with energy range of 1-6 GeV and a distance of ~2000 km is needed to observe 3 or more oscillation nodes.
2) The *appearance spectrum of electron neutrinos* from the oscillation of $\nu_\mu$ to $\nu_e$ contains information about $\sin^2 2\theta_{13}$, $\delta_{CP}$, $\Delta m_{21}^2$ and the ordering of neutrino masses through the matter effect (i.e., $m_1 < m_2 < m_3$ versus $m_3 < m_1 < m_2$). It was shown in our references that the various parameters can be separated out and measured using only *a single detector* in the broad-band 1-6 GeV beam with the ~2000 km baseline.

3) The matter effect causes the conversion probability to increase with energy and is most pronounced at energies >3 GeV, whereas the effects of $\delta_{CP}$ fall as 1/E. Our references show that this energy dependence can be used to measure the value of $\delta_{CP}$ and $\sin^2 2\theta_{13}$ without requiring anti-neutrino data for the case of normal mass ordering. Neutrino and anti-neutrino data together, will be needed to cover both possibilities of the mass ordering, and will lead to definitive result on CP-violation and precision measurement of the CP parameter $\delta_{CP}$. The energy dependence becomes larger for longer baseline distances and it is therefore advantageous to perform the experiment with a *very long (> 2000 km) baseline*, because we can then relax the requirements on systematic errors for the flux, the cross-sections, the other oscillation parameters, and for calculation of the matter effect.

In Figs. 1a, 1b, we illustrate the neutrino oscillation behavior and its dependence on baseline distance. In these graphs, we see the *appearance of electron neutrinos* from an initial beam of muon neutrinos as predicted by already-measured neutrino mass differences using an approximate formula that includes matter effects[4]. The figures are plotted for the case of perfect energy resolution and no background, ideal for illustrating the basic physics behavior. Also plotted is a practical wide-band neutrino flux spectrum, weighted by neutrino energy, able to be generated by a multi-GeV proton accelerator (BNL and Fermilab are depicted). These curves show the relative event yields as a function of neutrino energy, that could be expected in actual experiments, because the total neutrino cross section in this energy regime is proportional to energy.




*Figs. 1a, 1b – CP-violation phase behavior for broad-band neutrino beams from BNL and Fermilab to the Homestake Mine in Lead, South Dakota, a potential DUSEL site.*

Note that multiple nodes can be observed in the BNL $\nu_e$ spectra and that different values of the CP-violation phase, $\delta_{CP}$, are unambiguously distinguishable over this neutrino energy range in both examples with these baselines. This is an experimental feature that is unique to the very long baseline method using a broad-band beam.

<u>Physics Topic 2 – Improved Search for Nucleon Decay</u>

A feature of nearly every beyond the Standard Model (SM) theory in particle physics is the expectation that the proton will be unstable against decay into lighter, non-baryonic particles. Observation of these postulated, but as yet unobserved, decays would be of profound importance to our understanding of the origin and ultimate fate of the universe and would help document physical phenomena reachable by no other experimental means. We also know for certain that there must be *some* form of physics beyond the SM in order to understand and explain phenomena already well known. The highest-priority goal of particle physics is to discover precisely which version of non-SM behavior describes our universe and to measure its experimentally accessible properties. Observation of nucleon decay would count among the most important of such future particle physics achievements.

The large detector employed for neutrino oscillation experiments, discussed in Physics Topic 1, can be simultaneously used to conduct an improved search for nucleon decay, provided it is located deep enough underground (~4000 mwe). Water Cerenkov detectors have long been the dominant technology for pushing nucleon decay lifetime limits to where they are today. They provide the highest active mass to cost ratio, and they have good efficiency and background rejections for key proton decay modes. The UNO Collaboration has described a water Cerenkov detector concept, UNO, that would be sensitive to the postulated proton decay mode, $p \rightarrow \pi^0 e$ at the level of $10^{35}$ years, about an order of magnitude beyond the present experimental limits. In their written documents, the UNO group point out that this advance in sensitivity for detection of proton decay puts the UNO detector within range of a significant number of theoretical predictions for non-Standard Model nucleon decay[8]. Other groups have begun to develop alternate concepts for detecting nucleon decay, such as a liquid argon tracking detector in the 100 kT class[9]. This type of detector would be sensitive to the $p \rightarrow K^+ \bar{\nu}$ mode with higher efficiency than a water Cerenkov detector and could claim sensitivity in the $10^{35}$ years range.

Physics Topic 3 – Observation of Natural Sources of Neutrinos

All of the detector technologies we consider will lead to enhanced detection and study of neutrinos from natural sources such as the Sun, Earth's atmosphere and lithosphere, and past and current supernova explosions. There may also be previously unsuspected, natural neutrino sources that appear when the detector mass reaches the hundreds of kilotons scale. The liquid scintillator technique is of particular note here because it could allow the detection of low energy antineutrinos from Earth's lithosphere.

Solar neutrinos have already been observed in the Super Kamiokande[10] and SNO detectors[11]. If the large detector concepts discussed here result in construction of the underground experiment, it may become possible to increase the observable event rate high enough to clearly observe spectral distortion in the 5 to 14 MeV region. One could also measure the as yet undetected hep solar neutrinos (with end point of 18.8 MeV) well beyond the $^8$B endpoint (~14 MeV). Better determination of the solar spectrum as well as detection of the day-night effect with high statistics would represent a significant advance in the evolution of solar nuclear physics measurements.

The observation of supernova neutrino events in a large neutrino detector of the type being discussed in this proposal is straightforward and has historical precedent. The SN 1987A supernova, in fact, was seen by *two* large water Cerenkov detectors (5kT and 2.1 kT, respectively) that were active in proton decay searches at that time[12]. The predicted occurrence rate for neutrino-observable supernovae (from our own galaxy and of order 10 kpc distant) is about 1 per 20 years, so events will be very rare[13]. However, the information from a single event, incorporating measured energies and time sequence for tens of thousands of neutrino interactions, obtained by a very large neutrino detector, could provide significantly more information than has ever been obtained before about the time evolution of a supernova. With some 20-100 times the sensitive mass and, hopefully, a lower neutrino energy threshold (a few MeV), the energy and arrival-time spectra would have statistical power that the earlier detectors could not provide. Although this research topic may not be sufficient to motivate construction of its own detector, it provides increased science potential at no additional cost to the integrated program we are discussing here.

The continued study of atmospheric and solar neutrinos in the large underground detector will provide useful additions to the program carried out so successfully by the Super Kamiokande Experiment. The factor of 20 increase in detector fiducial mass will allow statistical improvements in all the topics studied and, perhaps, the emergence of new scientific topics. Statistical clarification of the day-night effect for solar neutrinos is one topic that will benefit from the strongly improved statistics. Other natural sources of neutrinos, such as relic supernova and lithospheric neutrinos, have not yet been studied extensively and could, in principle, be observed by the new detector concepts we consider below. An initial result in this area has recently been announced by KamLAND. Typically, the neutrino energies for these processes are below 10 MeV and are sensitively dependent upon the low-energy threshold capability of the new detectors. The liquid scintillator detector concepts we address are likely to have the best opportunities for advancing these topics, but liquid argon detectors could also contribute.

Finally, we note that there may be galactic sources of neutrinos that are of lower energy and greater abundance than the ultra high-energy neutrino sources to be explored by detectors such as the 'Ice Cube' Cerenkov detector now being constructed deep under the Antarctic ice sheet by an NSF sponsored collaboration. Galactic neutrinos have a natural source in inelastic nuclear collisions through the semi-leptonic decays of charged secondary pions. This source is expected to be of comparable intensity and energy distribution to the high-energy photons that are born from neutral pion decays in the same collisions[14]. Such neutrino sources, currently not detectable with Super Kamiokande, could be seen by a mega-ton class neutrino detector that runs for several decades. Such a scientific scenario is consistent with the DUSEL scientific mission.

<u>Relationship of the Physics Topics to the DUSEL Project</u>

A large detector facility located in the DUSEL is the optimum way to pursue all three of the above physics research goals. The important technical capabilities for such a detector are its fiducial mass, energy threshold, energy resolution, muon/electron discrimination, pattern recognition capability, time resolution, low-radioactivity detector environment, and depth of the underground site of the detector. The capital and operating costs for the detector are also a serious concern. The fiducial mass requirement derives from the precision sought for the CP-violation measurement (assuming that the value of $\sin^2 2\theta_{13} > 0.01$) and from the sensitive target mass needed to detect nucleon decay. A measured uncertainty of ~10-20% on the CP phase will require a detector in excess of 100 kT, since current technology limits the proton beam power to less than about 2 MW. For nucleon decay, it is clear that improvements in the sensitivity of the Super-Kamiokande detector, either a detector with much greater fiducial mass, or with much better efficiency, (or both) is needed to advance this field. The efficiency can be improved by employing more advanced detection techniques for some of the limited set of potential nucleon decay modes currently targeted. Therefore, a very large detector that is able to combine the measurement of accelerator-based neutrino oscillation parameters with a sensitive new search for nucleon decay, presents a very compelling component for the DUSEL science mission.

For the neutrino oscillation physics that we propose here, we noted that it is important to obtain good energy resolution on the neutrino energy, excellent pattern recognition, and a low energy threshold. The required energy resolution can be achieved by separating quasi-elastic scattering events, with well-identified leptons in the final state, from the inelastic charged-current and neutral-current events. If a very fine-grained detector (such as a liquid argon TPC) is used, it might be possible to use all of the charged current events and still obtain adequate energy resolution. One of the key questions that remains to be answered is how well quasi-elastic events for muon and electron neutrinos can be separated from other background events. A second important question is what statistical gain can be realized if a fine-grained detector uses a larger fraction of the charged current events. We also note that the absolute energy scale calibration in the detector is important and will require careful study to provide the lowest systematic error with a practical calibration system. Obtaining definitive answers to these detector performance questions constitutes an important goal of the event simulation and event reconstruction software R&D that we propose here.

Lastly, the energy threshold and the depth of the detector will determine the low-energy and low-rate capability of the detector for the detection of solar and supernova neutrinos, and for detection of atmospheric neutrinos, lithospheric anti-neutrinos and diffuse relic neutrinos from long past supernovae. The DUSEL is expected to provide sufficient depth for these purposes, however, a detailed study of the trade-offs in depth versus physics capability is needed for each of the technologies considered. Such studies will greatly benefit from the availability of the software products that will be produced by the R&D discussed in the tasks below.

[4] *M. Diwan et al., Phys. Rev. D. 68, 012002 (2003).*
[5] *M. Diwan, "The Case for a Super Neutrino Beam". Proceedings of the Heavy Quarks and Leptons Workshop 2004, San Juan, Puerto Rico, 1-5, June (2004). hep-ex/0407047.*
[6] *W. Marciano, "Extra Long Baseline Neutrino Oscillations and CP Violation", arXiv:hep-ph/0108181 v1, 2001.*
[7] *A. Strumia & F. Vissani, hep-ph/0503246 IFUP-TH-2005-06, Mar 2005.*
[8] *UNO EOI, http://nngroup.physics.sunysb.edu/uno/publications.shtml*
[9] *LAr Detector homepage, http://www.aquila.infn.it/icarus/exp.html*
[10] *Super Kamiokand detector homepage, http://www-sk.icrr.u-tokyo.ac.jp/sk/index_e.html*
[11] *SNO detector homepage, http://www.sno.phy.queensu.ca/*
[12] *C.B. Bratton et al., Phys. Rev.* ***D 37,*** *3361 (1988); K. Hirata et al., Phys. Rev.* ***D 38****, 448 (1988)*
[13] *M.L. Constantini and F. Vissani, e-Print Archive: astro-ph/0508152*
[14] *T. Araki, et al., Nature Vol 436, No. 7050 (2005) p499.*

## 2.0 Detector Technologies:

There are several competitive detector concepts and supporting technologies proposed for the very large, next generation neutrino and proton decay detectors currently under intensive study. The most promising designs at this point in time envision a megaton-scale water Cerenkov detector, such as the detector design proposed by the UNO Collaboration[8], and a 100kT, liquid Argon (LAr) Time Projection Chamber (TPC). Also, other new detectors, based on the continued development of liquid scintillators (LS) as a technology base, are of interest for next-generation reactor and neutrino cross section measurement experiments as well as potential applications in the very large detector arena, where LS might compete with the water Cerenkov and LAr technologies. To refine the merits and prospects of these three promising directions for neutrino detector development, we propose a program of detector-focused R&D to be carried out by BNL and university groups that have joined together to address the most pressing R&D questions in an efficient and collaborative manner. In some R&D areas we have reached agreement among groups to directly collaborate. In other areas, there is a cooperative relationship that allows separate R&D programs to be pursued with active coordination and mutual communication about projects and results. We will briefly describe our proposed R&D opportunities and their respective applications below, pointing out how each technology could potentially satisfy the science requirements described in the physics discussion above.

### 2.1 Water Cerenkov Detector Studies:

In this section, we discuss the next useful R&D steps that could be taken for further advancing the water Cerenkov method and its technology. This proposal will focus on two general directions, both of which are needed and both of which can be pursued productively in parallel. The first direction, one in which BNL and others have already initiated R&D activities at a low level commensurate with very limited resources, is focused on the creation of new simulation and event reconstruction software that will provide critically needed capability to relate different detector designs and technologies, principally for water Cerenkov detectors, but with useful capabilities for simulation of other detector methods as well. The new software products will be used to relate performance of the various detector concepts to the physics goals described in Section 1 above. The second direction features a hardware R&D plan to foster innovative improvement of photon sensors that will advance the current state of the art, the long used technology that employs classic single-channel photomultiplier tubes to detect neutrino events in water Cerenkov and liquid scintillator detectors. A number of very interesting new technologies are being brought forward that, with a little properly applied encouragement, could greatly advance the state of the art in neutrino detectors. We elaborate on these two R&D directions here.

<u>Software Development:</u> Dr. Chiaki Yanagisawa at Stony Brook University has performed a realistic study of rejecting neutral current background to $\nu_e$ signal events in a water Cerenkov detector for the BNL very long baseline neutrino oscillation experiment (VLBNO). The study was carried out using the Super-Kamiokande water Cerenkov detector simulation, combined with newly developed event reconstruction techniques. The

preliminary results of these studies indicate that the neutral current backgrounds in a water Cerenkov detector can be reduced to a level below the intrinsic beam background of electron neutrinos[15]. Improvements due to Yanagisawa's novel reconstruction software techniques allow $\pi^0$ events (which often produce double, overlapping rings or one dominant and one faint ring) to be better recognized and suppressed. As a side product many proton decay modes with $\pi^0$ decay products may benefit from these sophisticated analysis improvements. More study is needed and further improvements are expected. The study just described was carried out using the full Super-Kamiokande water Cerenkov detector simulation using the BNL broad-band neutrino beam spectrum, incorporated by re-weighting atmospheric neutrino spectrum which is already included in the Monte Carlo program. Additional studies using a detector simulation of the mega-ton scale water Cerenkov detector[8] coupled with a VLBNO simulation based on the GLoBES software package[16] are currently underway. Details of BNL's R&D planned tasks for completing the UNO water Cerenkov detector simulation with realistic reconstruction software and the GLoBES VLBNO project will be discussed in Section 3.1.

<u>Hardware Development:</u> Current water Cerenkov detector technology is based on light detection using large-area photo-multiplier tubes (PMT) such as the 20" Hamamatsu PMTs used in Super-Kamiokande. For example, the UNO detector would require 56K 20" PMTs to instrument its fiducial region. Using the Super-Kamiokande 20" PMTs, it would take 8 years to manufacture enough PMTs for UNO at a cost of $155M; this represents about 30% of the total cost of the detector (including civil engineering costs).

Noting this history, we observe that:

- preliminary simulation results indicate that a water Cerenkov detector is a feasible technology choice for the VLBNO program;
- a substantial fraction of the cost of a water Cerenkov detector is driven by the cost of the PMT light detection technology used;
- improvement of photo-detection techniques and detector capabilities in water Cerenkov (and liquid scintillator) detectors could substantially improve event reconstruction.

With these observations in mind, BNL proposes to embark on a program of R&D into large area light detection technology for water Cerenkov and liquid scintillator detectors that could substantially reduce the cost of instrumenting such a detector and improve event reconstruction performance. For example, in the water Cerenkov technology, improvements in water clarity and reductions of reflective detector surfaces are expected to improve event reconstruction. Initial studies[17] show approximately 7-25% improvement in efficiency, depending on mode, can be expected for an ideal detector. To carry out the R&D program intent, we suggest that there are three potentially productive paths to pursue for water Cerenkov-based detector R&D:

1: Reduce the cost of manufacturing PMTs through SBIR and other efforts directed towards development of industrial techniques to mass-manufacture large vacuum tubes; or, alternatively, use larger numbers of smaller tubes to cover the same active area;
2: Develop a testing facility that could be used for both new and old ideas for photosensors. For example, a number of efforts are under way to abandon the old vacuum tube technology and develop solid-state solutions to light detection with high quantum efficiency, large-area coverage and position sensitivity. These require testing and comparison to PMTs;
3: Pursue hybrid PMT technology, combining traditional vacuum technology with solid-state devices like silicon pixel detectors, avalanche photodiodes and scintillators. An advantage of this approach is the ability to have multi-pixel readout. Such a readout combined with appropriate optics could dramatically improve event reconstruction.

<u>Path 1 Efforts</u> - Several companies are already pursuing this path, most notably:

i) Burle Industries is working on Phase II of a DOE SBIR to develop 20" PMT manufacturing at a cost of $0.75/cm^2$ of active area including VDN and cabling (presentations[18] at NNN05).

ii) Photonis, Brive, France has carried out a study on the cost savings achievable by instrumenting large surface areas using smaller PMTs. They find that the instrumentation cost using 50,000 20" PMTs at Euro 2500/PMT is Euro 125M, whereas the cost of instrumenting the same area using 135,000 12" PMTs at Euro 800/PMT is Euro 108M (presentations[18] at NNN05).

As shown above, efforts by various PMT manufacturing companies, aimed at reducing manufacturing costs of traditional PMTs for large area detectors, are already yielding substantial savings. Additional support of industrial efforts, through SBIR grants in partnership with BNL and University groups, is expected to be a critical element in driving down the manufacturing costs. We also note, along these lines, that the cost of the PMT scaling could be mitigated by using lower photo-sensor coverage while not adversely impacting some nucleon decay modes or severely degrading the detector's VLBNO event recognition/background rejection performance. Comparisons[19] between Super Kamiokande-I (40% PMT coverage) and Super Kamiokande-II (19% PMT coverage), have shown that nucleon decay searches for the $p \rightarrow \pi^0$ e mode do not suffer greatly. Other modes, such as the SUSY favored $p \rightarrow K^+ \ \nu$, employing an event signature that includes a faint 8 MeV photon, still require further simulation checking. Costs could also be mitigated by using more, smaller photo-sensors[20]. This idea has several potential benefits: reduced dependence on vendor; a higher photoelectron/dollar ratio; better timing (which leads to better vertex resolution); and better single photoelectron resolution. Finally, having more photo-sensors is expected to provide better event reconstruction performance due to more finely imaged details of the Cerenkov ring structure. These issues can only be decided by vigorously pursuing R&D, both on event and reconstruction simulation and on hardware development .

Path 2 Efforts – Existing Water Cerenkov detector technology and techniques have already proven themselves. Nevertheless, at megaton scale unexpected backgrounds could arise for both the nucleon decay search and accelerator neutrino oscillation signals. More aggressive technical approaches are, therefore, also attractive R&D targets as we discuss below.

In addition to reducing manufacturing costs, it is highly desirable to improve the capabilities of the photo-detectors themselves to enhance event reconstruction and particle identification. Data from laboratory tests of various photo-detection technologies can be immediately implemented in our detector simulation and event reconstruction efforts for assessment of the physics sensitivities using different photo-detector technologies. Rapid feedback will be an extremely important input for the timely incorporation of the technology progress made by these efforts into the evolving detector design concepts.

In many applications in particle and nuclear physics experiments, it will be advantageous to determine the propagation direction of individual scintillation or Cerenkov photons. In a large particle-physics detector (for example, the Super-Kamiokande detector), photons are detected by photo-multiplier tubes. If these tubes were to be replaced by large acceptance optics coupled to high spatial resolution photo-sensors, then the direction of each detected photon could be better reconstructed. Knowledge of the location of the sensor and its ability to determine the photon direction with good resolution will greatly aid the reconstruction of events. The added information about the photon directions will also improve particle identification, energy resolution, and reconstruction of events with multiple particles. The critical elements in the above scheme are appropriate optical elements (with large spatial and angular acceptance) and a position sensitive photo-sensor with good quantum efficiency over the visible wavelengths, resolution of the order of few mm, single photoelectron detection efficiency and good timing resolution. Preliminary studies of these concepts have been performed at BNL. These studies include simulation of neutrino events in a detector instrumented in the above manner as well as studies of the optical design, either using lenses or mirrors. Much more detailed studies are needed as part of this R&D proposal.

A critical component in the R&D effort into light sensors for water Cerenkov applications is the existence of a test facility where sensors can be tested in realistic conditions. BNL has constructed a small water

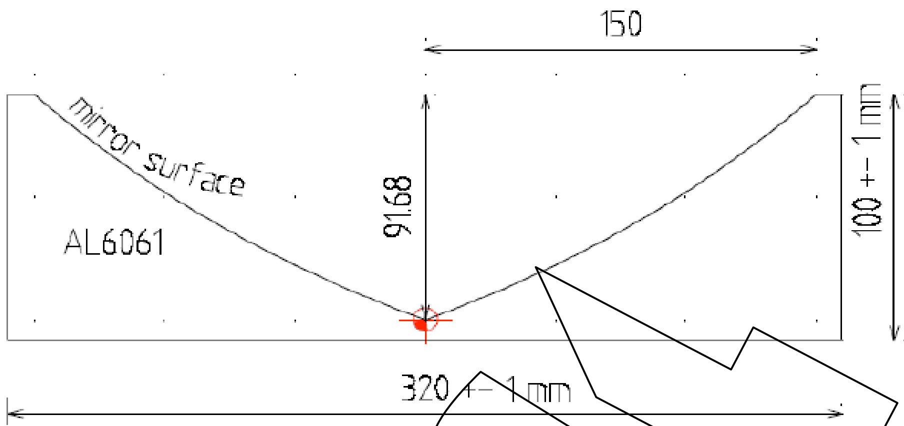



*Fig. 2 – Schematic of a mirror to focus Cerenkov light from vertical muons.*

Cerenkov test tank to measure Cerenkov light from vertical muons using a variety of sensors. Cerenkov light from cosmic muons was successfully detected in the prototype tank using a PMT as the sensor. The current tank has been built with off-the-shelf components operated at room temperature. Provisions have been made to change the temperature of the tank as well as control the water purity. Nevertheless, further investment is needed to develop a fully operating facility for testing various sensors and HV delivery systems in a water filled environment. In particular:

i) BNL has made a design of a light-focusing mirror that will improve the light collection efficiency for Cerenkov light emitted from mostly vertical muons entering the tank. The shape and size of the prototype mirror chosen is illustrated in Figure 2. The cost of manufacturing 2 small proto-type mirrors from industry is estimated to be around \$20,000 each because of the small quantity. One of our collaborators, Mel Ulmer (Northwestern University) can manufacture the same devices in his laboratory with novel techniques that could be useful for large scale production. This could be an ideal way to both create the mirrors that we need for immediate use as well as fund R&D into advanced mirror fabrication techniques that could lead to mirrors that are stable over 10-20 years in a deep underwater environment.
ii) More investment in a water filtration and purification system is needed.
iii) Funding for the mechanical design and building of a large water tank for proto-typing the response of several large area sensors simultaneously is needed.

As an example of the use of such a facility we describe some of the current R&D we are pursuing. The group at BNL is performing R&D under Phase II of a DOE SBIR to develop large-area high-gain avalanche photodiodes (APD) for use as photo-sensors in a variety of environments. The research is being carried out in partnership with Radiation Monitoring Devices Inc (RMD) of Watertown, Massachusetts. APDs have higher quantum efficiencies at visible light wavelengths compared with PMTs, and the use of pixellated detectors will allow position sensitive measurements which could be useful for the imaging readout described earlier. In Phase I of the DOE SBIR grant, RMD has successfully manufactured 4.5 x 4.5 cm$^2$ APDs with gains of up to 1000 . However, the high capacitance of the traditional version of the APD causes the noise level to be high for large area devices. The high noise level means they have limited use in applications that demand single photon counting ability, such as water Cerenkov counters.

We are currently measuring the gain, noise and timing properties of various large-area/high-gain APDs from different manufacturers. We have identified various improvements to the manufacturing process for these large-area, high-gain APDs to reduce some fraction of the noise and improve the leading edge time of the signal. As part of the same R&D, a water-proof packaging and high voltage (HV) delivery system has been

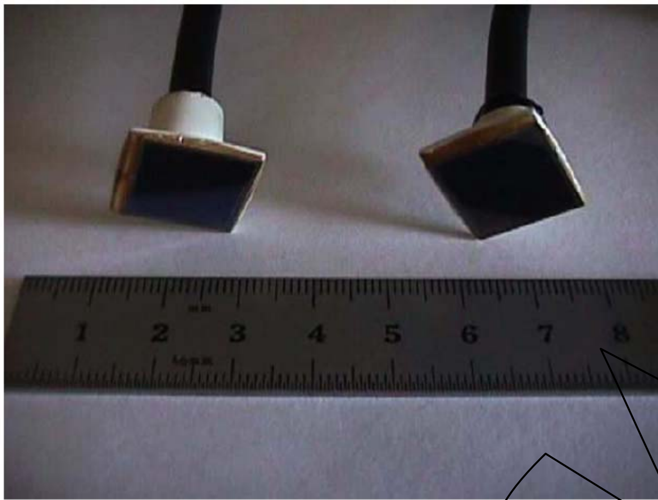


*Fig. 2 - 1.5 x 1.5 cm APD prototype from Radiation Monitoring Devices Inc, Watertown, Mass.*

developed (by RMD Inc.) to allow APDs to be immersed in water. Fig. 2 is a photograph of 2 water immersible APDs, we are currently engaged in testing these devices for gain, noise, long term stability, and sensitivity to Cerenkov light.

Path 3 efforts - Hybrid PMT technologies have the potential to reduce manufacturing cost while preserving the excellent single photon detection capabilities of PMTs. When combined with appropriate optical components they could also enhance performance with the addition of direction sensitive capability for photons. One promising direction, advocated by Ypsilantis and collaborators, is the Aqua-Rich[21] approach, where the resolution on Cerenkov rings becomes ~3% as compared with the >50% obtained in Super-K with very large PMTs. The large photocathode area, fine-grained approach of Aqua-Rich, should yield precise tracking and particle identification in the water Cerenkov detector as well as good electromagnetic energy resolution for electrons and photons [$\sigma_E$ / E ~12%/√E (GeV)].

Multichannel photomultiplier tubes for Ring Imaging Cerenkov detectors are under study for High Rate collider experiments (LHCb). For the US Long baseline neutrino program we would like to begin evaluation of the PMT options in conjunction with optics simulations. An example of a hybrid technology considered at BNL is The Hybrid Photo Detector (HPD). The HPD consists of PIN diodes integrated in a vacuum tube.

The HPD is equipped with a photo-cathode in which the photons are converted into photoelectrons. Unlike photomultipliers , after acceleration, the photoelectrons bombard the diode and secondary electrons are created inside the diode. By using appropriate preamps a measurable signal is obtained. Both single pixel and multi-pixel devices are available. The pixel position can be used to determine the position of the photon incident on the photo-cathode. This technology has been pioneered by the Dutch manufacturer DEP, but Weilhammer's lab at CERN also has been manufacturing large area (10 inch) Hybrid PMT's. The hybrid PMT is a potentially less expensive alternative to previously available multi-anode PMT and is far superior for single photoelectron counting. With an accelerating potential of, typically, 15 KeV between the photocathode and the silicon target, one obtains of order 5000-6000e signal electrons per photo-electron, as compared with electronic noise levels of 400 e; consequently, the signal to noise is ~12:1. Typically, readout of these devices has a per-channel electronics cost of about $2. In addition to good signal to noise and low cross-talk, these HPDs feature a timing resolution of ~1nsec. The gain of the HPD could be significantly increased by replacing the PIN diodes with high gain avalanche photo-diodes. Prototype 5" and 13" HPDs, each with a single APD readout, have been manufactured by Hamamatsu- Photonics (Figure 5). Initial tests

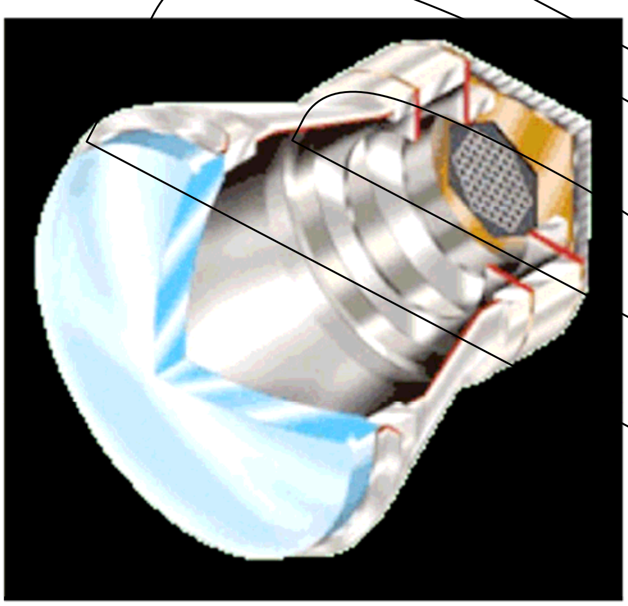


*Fig. 4 – Hybrid DEP PMT*

indicate that the device has excellent single photon sensitivity as shown in Figure 6. Additional funding is needed to purchase several prototypes of the Hamamatsu HPDs and to commission the manufacturing of HPDs with multi-pixel APDs. Funding in support of the HPD testing effort is needed and is strongly coupled with the Strategy 2 effort for developing a test facility and optics for water Cerenkov photo-sensors. The building of an in-water Cerenkov testing facility (described above) and providing funding for dedicated Laboratory personnel to design, build and maintain the readout electronics and HV delivery systems is needed to advance this program.

In very large water Cerenkov and liquid scintillator detectors, PMTs and hybrid vacuum tube technologies are subject to large pressures across their surfaces. For example, in a water Cerenkov detector the size of UNO, photosensors at the bottom of a 60m column of water experience a pressure of 85psi. Photo-sensors based on vacuum tube technologies need extensive testing under pressure to decide their feasibility for use in a mega-ton detector. In addition to a water test facility, a pressure chamber will need to be designed and built to assess the mechanical robustness and hardiness of hybrid photosensors under pressure.

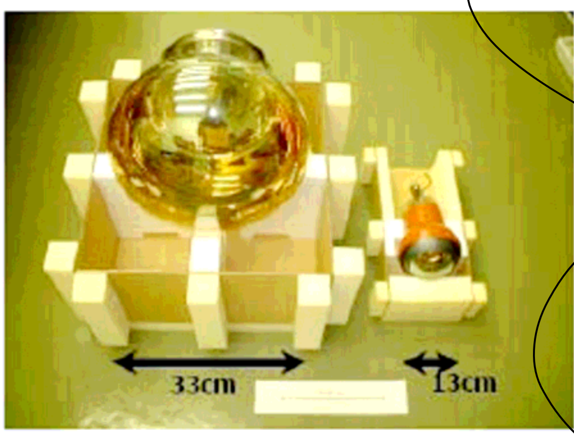



*Fig. 5 – Hammamatsu Hybrid PMTs*

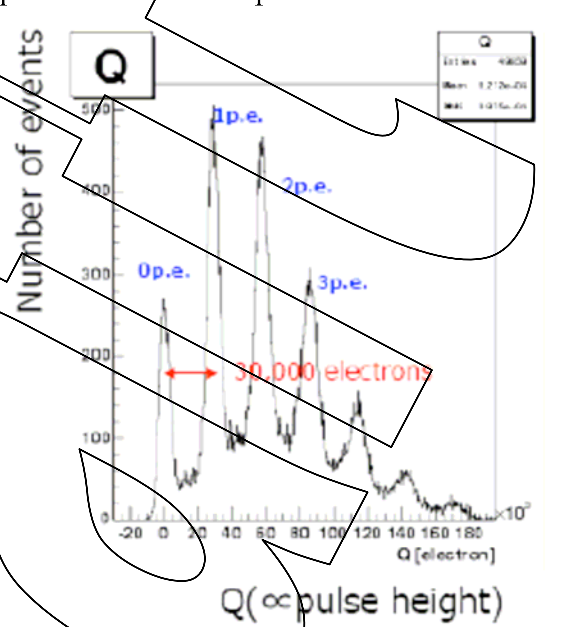



*Fig. 6 – Few Photon Pulse-height Spectra*

[15] *C. Yanagisawa, Stony Brook University. Presentation at NNN05, NuFACT05;* http://nnn05.in2p3.fr/trans/yanagisawa.ppt
[16] *P. Huber, M. Lindner and W. Winter, "Simulation of long-baseline neutrino oscillation experiments with GLoBES, Comput. Phys. Commun.* ***167****, 195 (2004); arXiv hep-ph/0407333; HEP-PH 0407333.*
[17] *T. Kobayashi, Presentation at NNN05, http://nnn05.in2p3.fr/schedule.html*
[18] *Presentations at NNN05;* http://nnn05.in2p3.fr/schedule.html
[19] *Shiozawa NNN05 reference*
[20] *Esso Flyckt, Photonis, Nufact05*
[21] *P. Atonioli et al. Nuc. Instr. and Meth.* ***A433*** *(1999) 104.*

## 2.2 Liquid Scintillator Improvements:

Research and development is needed now for new liquid scintillator materials for potential use in three important neutrino physics applications: 1) a high-precision reactor neutrino detector to measure, or reduce the upper limit on, the oscillation parameter $\sin^2 2\theta_{13}$; 2) a novel mid-size detector for short-baseline neutrino measurements; 3) a potential application in a 100 kT class experimental detector for long baseline neutrino oscillations measurements and nucleon decay search physics.

To optimize the physics capabilities of the reactor experiment detector, R&D is needed for new liquid scintillator (LS) materials. The resulting new liquid scintillators could also have applications for very large neutrino detectors at a later stage of neutrino oscillations research. The R&D tasks proposed here will be carried out by the BNL Chemistry Department's Solar-Neutrino/Nuclear-Chemistry Group, together with proposed collaborations with faculty members in the Physics Department of Indiana University for tasks (2) and (3), and with faculty members in the Physics Department of Virginia Tech University for task (3). These groups are well placed to pursue the proposed R&D in a way that capitalizes on each group's strengths.

The BNL Group has performed R&D with liquid scintillators (LS) for the past four years, especially with regard to the difficult task of preparing metal-loaded liquid scintillator, M-LS. This work was first done in collaboration with R. S. Raghavan (formerly of Bell Labs-Lucent Technology, now at Virginia Tech University) in connection with the proposed LENS low-energy solar neutrino detector. More recently, the BNL Group has independently done R&D with Gd-LS for the task (1) $\theta_{13}$ experiments. As a result, the Group has developed extensive expertise in a variety of organic-chemical synthesis and purification procedures for preparing the LS, and continues to seek improvements in its methods. There are very few groups worldwide that have this expertise. There are two main efforts going on in the BNL Group: the first, development of the Gd-loaded liquid scintillators for detection of neutrons produced by antineutrino interactions in task (1), has made a lot of progress during the past 1-2 years; the second, application of the new scintillators to very large experimental detectors, tasks (2) and (3), is an extension of these efforts for the longer term.

The Indiana University Group seeks, in collaboration with BNL, to build a prototype fine-grained neutrino detector and to use it to investigate the properties and capabilities of liquid scintillator. This effort will benefit the US neutrino physics program by demonstrating the viability of a new type of detector that is suitable for the short-baseline neutrino measurements required to support future long-baseline neutrino oscillation experiments. It will also be capable of investigating various types of liquid scintillators that are candidate materials for large reactor or deep-underground experiments.

As part of this proposal, BNL also plans to collaborate with the Hyper Scintillation Detector working group to study the design of a detector with 50-100 kT of liquid scintillator. Along with technical issues that the liquid scintillation technology approach must address, we will compare the capabilities of the liquid scintillation method with the other techniques, making use of the simulation and analysis software products that are proposed as an R&D topic in Section 3.1 of this proposal. An advantage of the liquid scintillation technique is the low energy threshold that can potentially be reached (possibly as low as ~0.1 MeV) and the ability to detect particles below the Cerenkov radiation threshold. A second significant capability of the liquid scintillator detector is its ability to tag anti-neutrinos through the detection of time-coincident neutrons from inverse-beta-decay reactions on protons; this is a well-established experimental technique. The KAMLAND detector[22] with 1.2 kT of fiducial mass has demonstrated the feasibility of the technique. We would like to examine the next feasible steps for this detector technology as they would apply to a very large neutrino detector.

As part of this proposal we would like to carefully examine the pattern recognition capabilities of a very large liquid scintillation detector for high-energy neutrino interactions as well as for detecting nucleon decays. It is clear that this technology could be competitive with other techniques for study of anti-neutrinos (thru tagging) and special decay modes such as ($p \rightarrow K^+ \bar{\nu}$). Moreover, the unique capabilities of liquid scintillation technology could offer a complimentary approach to Cerenkov and Liquid Argon technologies by extending the scientific scope to topics with low-energy signals such as geo-physics and cosmology phenomena. For example, the structure of the earth's crust and mantle could be elucidated by global observation of anti-neutrinos emitted by the distributed radioactivity in these regions. The basic energy budget of the earth addressed by geo-neutrino spectroscopy is of particular relevance to the DUSEL science portfolio. A liquid scintillator based detector also offers the opportunity for a yes/no test of the hypothesis of a still-operating fission reactor at the center of the earth by searching for the "smoking gun" of the geo-reactor antineutrino signal. The clean antineutrino tagging capability will also allow experimental observation of anti-neutrinos emitted both in the precursor and explosion phases of a new supernova and, via detection and spectroscopy of the relic anti-neutrino background, from past supernovae. We believe that the

Hyper Scintillation Detector (HSD) approach should be an integral component of any R&D program for very massive detectors in future science programs, especially in the DUSEL context.

## 2.3 Liquid Argon Detector Improvements:

Over the past decade, there has been steady progress in the development of technology for tracking ionizing particles by using an electron drift system utilizing electric fields in liquid argon (LAr) followed by amplification of the collected charge and data recording by electronic methods[23, 24]. The further development of this technology from the 1kT detector scale to the 100 kT detector scale could have a dramatic effect on the conceptual design for a megaton-scale neutrino detector with advanced nucleon decay search capabilities. This conclusion derives from the observation that it may be possible to use for oscillation analysis, not just the *quasi-elastic*, charged-current neutrino interactions for measuring the incoming neutrino energy in a very long baseline neutrino program, but also most (or all) of the *inelastic* charged current neutrino interactions. If this possibility can be realized in the conceptual design of a practical 100 kT neutrino detector, a five-fold increase in the useable event rate for neutrino oscillations analysis could be realized and this detector would become very competitive with a 500 kT water Cerenkov detector by making up the water detector's fiducial mass advantage by means of a larger useable charged-current event sample. Similar considerations apply to an advanced search for proton decay via a large number of possible processes, $n \rightarrow \pi^- l^+$, $n \rightarrow K^- l^+$, $n \rightarrow K^0 \bar{\nu}$ and $p \rightarrow K^0 l^+$ where $l^+$ is an electron or muon, as well as, $p \rightarrow \pi^0 e^+$ and $p \rightarrow K^+ \bar{\nu}$ that can also be detected in a water Cerenkov detector. This increase in the number of visible channels relative to a water detector of the same fiducial mass could increase the sensitivity of the LAr detector for nucleon decay significantly.

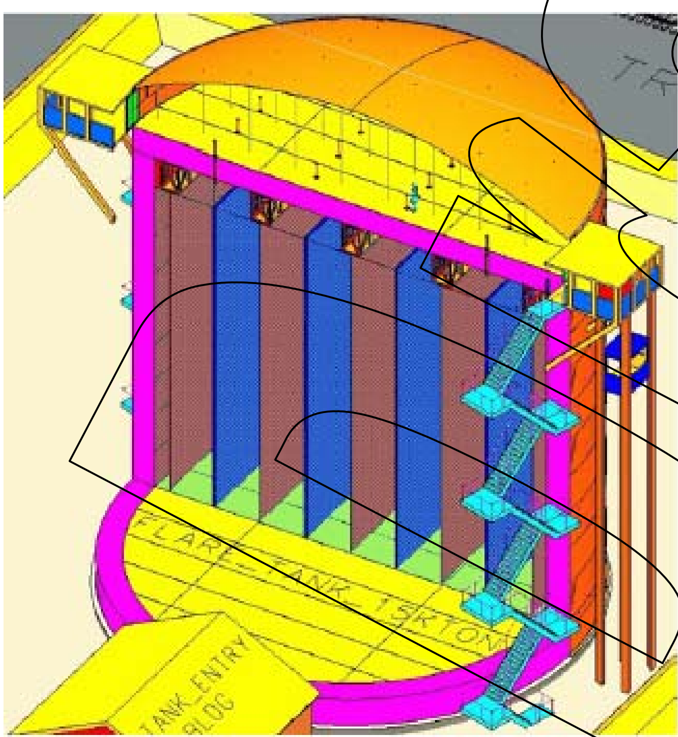



*Fig7. Schematic of 15 kT Liquid Argon Detector showing outer tank, inner tank, wire and cathode planes, as well as signal chimneys.*

The concept of a large liquid-argon time projection chamber for studies of neutrino physics from both accelerator and astrophysical sources, and also of proton decay, was introduced by Rubbia in 1977[23].

The development of this technology has been championed by the ICARUS group, whose efforts to date have culminated in the construction of 300-ton detector modules that can be transported by truck[23]. Consideration of a 100 kT detector within a single cryostat began in 2001[25, 26], based on a minimization of cost for a large detector of fixed mass as a function of the number of its component modules[27]. Such a large device (Fig. 7), if built on the surface using the technology of the liquified natural gas industry (with support from the air-liquification industry) is estimated to have a similar cost per ton of a large water Cerenkov detector (and to be ~1/2 the cost per ton of a large liquid scintillator[28]. The opportunity to combine a long-baseline accelerator neutrino physics program with studies of neutrino astrophysics and proton decay cannot, however, be realized with a detector sited on the Earth's surface. The feasibility and safety of construction and operation of a large cryogenic detector at a deep underground site (Fig. 8) deserves attention, and is the key topic for R&D on liquid argon detectors in the present proposal. R&D towards a large liquid argon detector at a surface site will be pursued elsewhere cannot, however. A previous proposal to study issues related to an underground siting of a large cryogenic neutrino detector[29] was never carried out.

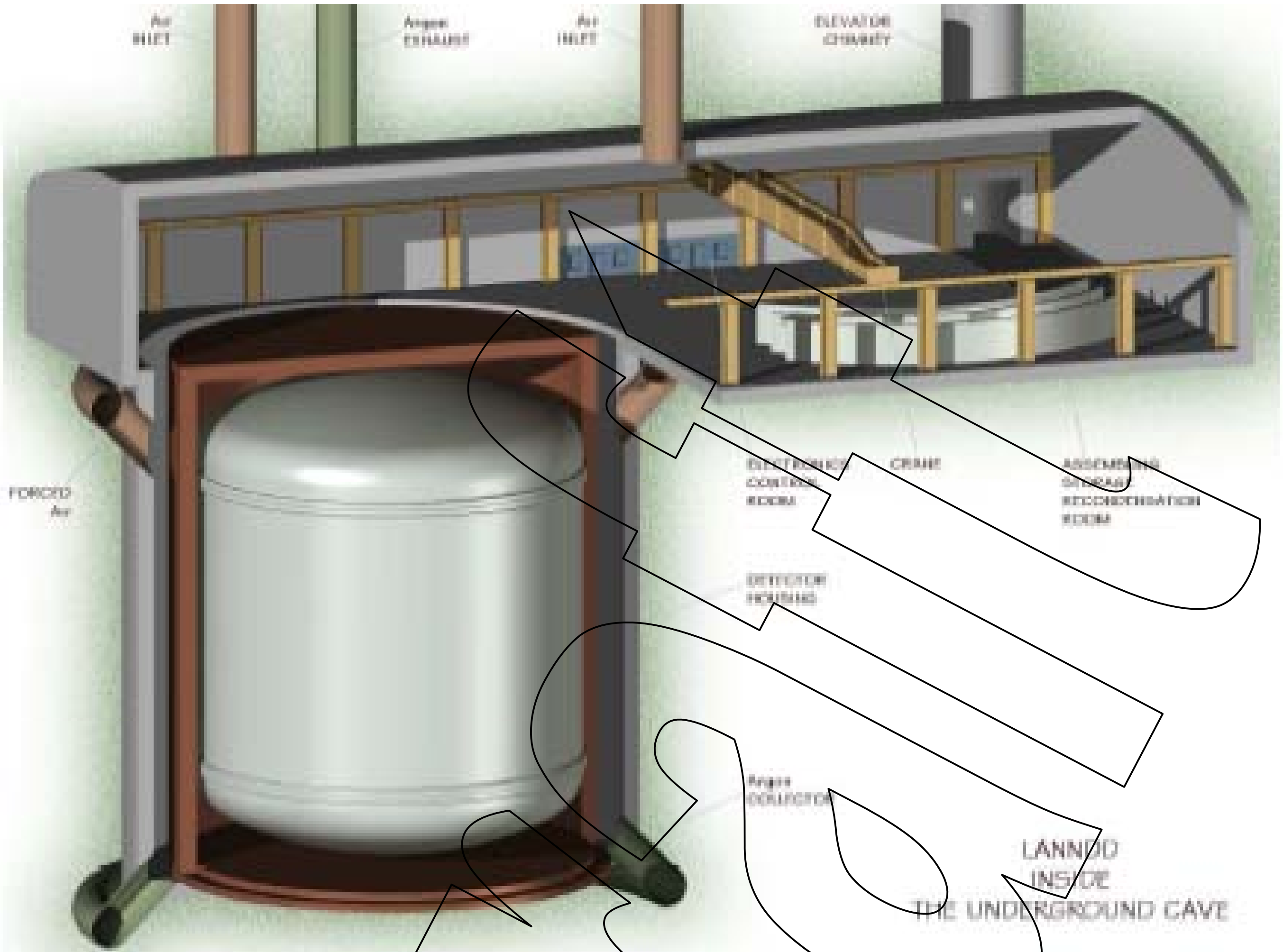



*Fig. 8. A possible configuration of a liquid argon TPC at a deep underground site.*

For practical reasons, some of the direct detector performance R&D issues would include:

- Verify that a 100 kT LAr detector, using all (or most) of the charged-current channels, can produce the same physics reach as a 500 kT water Cerenkov detector using only the quasi-elastic channel;
- Establish efficiencies for $\nu_e$ and $\pi^0$ background rejection in LAr;
- Verify that a LAr detector can operate with acceptable live-time for neutrino-beam based oscillation physics in the surface (or near-surface) cosmic ray background (ignoring proton decay);
- Establish a realistic cost estimate for a 100 kT detector based on current or reasonably achievable (conservative) technology.

In addition, there are significant safety and technical issues raised by a contemplated underground detector operated deep enough below the surface to avoid cosmic-ray generated backgrounds. In a LAr R&D program, there would be positive advantages if the work involved collaboration of the interested university and BNL physicists with the group at Fermilab[30] that is interested in liquid argon technologies. Such potential collaboration is being explored with Fermilab researchers interested in the R&D topics noted above.

## 3.0 Proposed Research and Development Topics:

### 3.1 Simulation and Software R&D

Task 1 - Neutrino Source Simulation Software

Detailed and flexible software simulation of the neutrino flux from a very long baseline, proton-driver source is essential for optimizing the beam line design and understanding the physics reach of the experiment. It is necessary to create this code in a way that it remains relevant for the foreseeable future. To allow fast implementation and to ensure adequate technical software support for the future, we plan to proceed within the GEANT4 simulation framework. We estimate that 1 FTE-year will be required to complete the initial software development and a part-time maintenance effort of 1 FTE-month per year, thereafter. At BNL, this proposed work can best be carried out with a mixture of existing, experienced neutrino research group members, together with a new post-doctoral associate or talented graduate student.

Proposed Work and Budget:
The projected software Task 1 R&D budget for the next three years for R&D comprises:

**R&D Task 1 – Budget by Fiscal Year**

| Budget Item | FY 2006 (FY06 $K) | FY 2007 (FY06 $K) | FY 2008 (FY06 $K) | Sum (FY06 $K) |
|---|---|---|---|---|
| Personnel* | 168 | 17 | 17 | 202 |
| Computing | 10 | 2 | 2 | 14 |
| Travel and Miscellaneous | 7 | 7 | 7 | 21 |
| **Totals** | **185** | **26** | **26** | **237** |

* Personnel needed: FY 2006, 1.0 FTE staff physicist/postdoc; FY 2007, 08, 0.1 FTE staff physicist/postdoc

Task 2 - Water Cerenkov Detector Simulation/Reconstruction

To confirm preliminary studies and provide a fully convincing demonstration that the Very Long Baseline Neutrino Oscillations (VLBNO) experimental concept is practically realizable and, arguably, the best next-generation neutrino oscillation experiment, requires a fully realistic software simulation as well as knowledge of realistic reconstruction efficiencies and background rejections for event analysis programs. To remedy current shortcomings, more effort is needed to complete and extend existing UNO Detector Monte-Carlo software and to develop an event reconstruction software suite. This work has started but needs to be accelerated. The proposed software effort is expected to continue into the construction and operating phase of a VLBNO scientific program. The proposed tasks could be accomplished by bringing visitors to BNL to work in close communication with experts here and at and/or by hiring a postdoctoral assistant. It will be advantageous for the same individuals to contribute to both tasks 1 and 2 which are closely-linked.

Proposed Work and Budget:
The projected software Task 2 R&D budget for the next three years for R&D comprises:

**R&D Task 2 – Budget by Fiscal Year**

| Budget Item | FY 2006 (FY06 $K) | FY 2007 (FY06 $K) | FY 2008 (FY06 $K) | Sum (FY06 $K) |
|---|---|---|---|---|
| Personnel* | 42 | 42 | 0 | 84 |
| Computing | 5 | 5 | 0 | 10 |
| Travel and Miscellaneous | 7 | 7 | 0 | 14 |
| **Totals** | **54** | **54** | **0** | **108** |

* Personnel needed: FY 2006, 07, 0.5 FTE postdoc

Task 3 - Background and Analysis Package for a Water Cerenkov Detector

The software developed in the tasks above is needed to understand and discriminate against background events arising from neutral-current neutrino events containing one or more $\pi^0$s. Conversion of a photon from the $\pi^0$s can simulate the recoil electron in charged-current signal events from $\nu_\mu$ to $\nu_e$ oscillations. The improved new background studies should be carried out independently of the software created at Stony Brook University (SBU) using Super Kamiokande Collaboration software, so that the proposed VLBNO/UNO simulation studies will benefit from the increased power and flexibility of the new VLBNO software with its full freedom to vary parameters and cuts to study and reduce backgrounds. The background studies proposed in this R&D task will use the software development described in the software R&D tasks above.

For tasks 1 to 3, we intend to fully co-operate with the UNO collaboration, of which we are members. Our main task partners will be the Stony Brook UNO group and the Colorado State University UNO group. The R&D plan we have presented assumes that our partners are also able to participate according to their strengths in this project.

Proposed Work and Budget:
The projected software Task 3 R&D budget for BNL for the next three years of R&D comprises:

**R&D Task 3 – BNL Budget by Fiscal Year**

| **Budget Item** | **FY 2006 (FY06 $K)** | **FY 2007 (FY06 $K)** | **FY 2008 (FY06 $K)** | **Sum (FY06 $K)** |
|---|---|---|---|---|
| Personnel* | 42 | 17 | 17 | 76 |
| Computing | 5 | 5 | 5 | 15 |
| Travel and Miscellaneous | 15 | 15 | 15 | 45 |
| **Totals** | **62** | **37** | **37** | **136** |

* Personnel needed: FY 2006, 0.25 FTE staff physicist; FY 2007, 08, 0.1 FTE staff physicist

Task 4 - Implementation of VLBNO Experiment in GLoBES

The Global Long Baseline Experiment Simulator[16] (GLoBES) is a software system that performs a fast simulation for LBL neutrino experiments. It allows for an easy comparison between, and combination among, various experiments. The GLoBES tool has become very popular among theorists to test the sensitivity of future neutrino oscillations experiments as well as study specific theoretical models for New Physics. The GLoBES program will act as a valuable basis for comparison among the detector technologies and capabilities described in the other sections of this proposal. GLoBES allows us to change individual parts of the experiment simulation and determine the effects on the physics performance. In Fig. 9, we see results from the current simulation of the VLBNO very large water Cerenkov detector obtained in GLoBES.

So far, the input files to GLoBES rely on preliminary fast simulations that parameterize detector performance. As part of the detector R&D, we would like to complete the study of all correlations and resolutions. Further work on complete detector simulations will be introduced into our calculations as they are completed.

One of the UNO collaborators at Stony Brook University (Dr. Chiaki Yanagisawa) has recently made much progress with a more detailed study to reduce the background levels by using Super-Kamiokande atmospheric neutrino event data, re-weighted to approximately match the VLBNO neutrino flux parameters. These important analysis results need to be incorporated into the GLoBES input for the VLBNO experiment. There is also an elaborate effort going forward to generate a full Monte Carlo simulation of, plus event reconstruction for, a 0.5 MT water Cerenkov detector. The resulting numbers, as well as any other future changes to the experimental setup and predictions, should be incorporated in the GLoBES.

Besides the proposed water Cerenkov detectors, other techniques such as liquid scintillator and liquid Argon are generally regarded as valid competitors for a very large neutrino detector. The outcome of any realistic simulation for the experimental realization of one or more of these technologies can go into GLoBES for an equitable comparison. It will ensure that any differences in the sensitivities observed are due only to the use of different technologies and not to different methodologies or assumptions about the experimental circumstances, e.g. the neutrino flux.

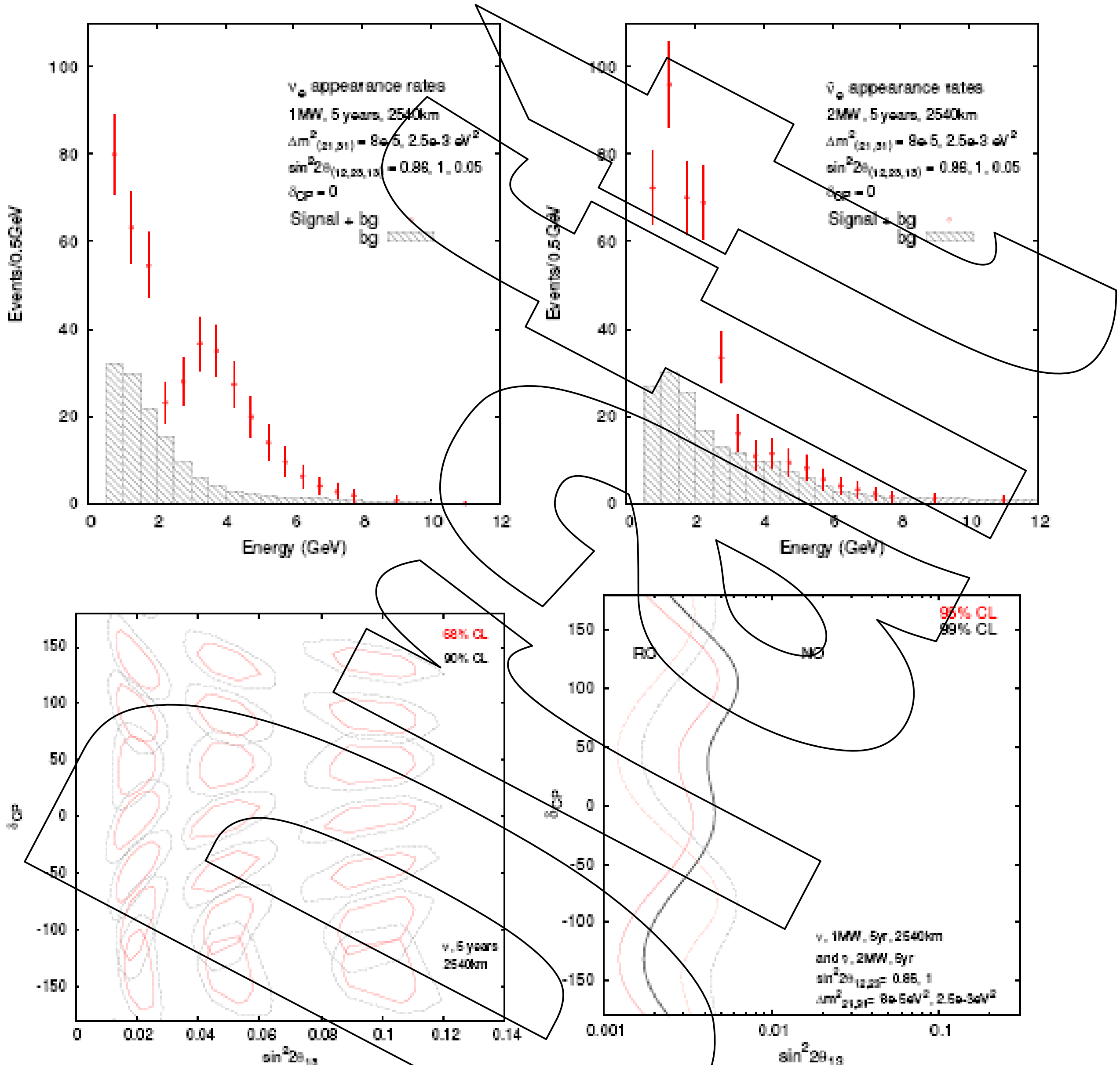



*Figure 9: The $\nu_e$ appearance spectrum for neutrino running (top left) and anti-neutrino (top right) for normal mass hierarchy, $\sin^2 (2\theta_{13}) = 0.05$ and no CP violation. The dashed histograms represent the background, while the dots include the signal. The expected sensitivities (bottom left) on $\sin^2 (2\theta_{13})$ and $\delta_{CP}$ result from 5 years of neutrino-only running for a wide range of true values and assuming normal mass hierarchy. The exclusion limit (bottom right) on $\sin^2 (2\theta_{13})$ at 68% and 95% C.L. for normal (solid lines) and reversed (dashed lines) hierarchy (assuming 5 yrs of neutrino and 5 yrs of anti-neutrino running) in the case that $\theta_{13} = 0$ for different values of $\delta_{CP}$. All results include a 10% error on the background normalization.*

As described in a subsequent proposal section, a number of reactor experiments are proposed to measure $\theta_{13}$. The reactor experiments will clearly affect the prospects of any later super beam experiment. Observation of the $\theta_{13}$ mixing angle by a reactor experiment will impact the strategy followed by the proposed VLBNO experiment. GLoBES allows for an easy and transparent comparison of the impacts among the different experiments.

Many aspects of the proposed R&D efforts in this document will improve our knowledge of the experiments' capabilities and should be incorporated in the GLoBES inputs. We propose that a dedicated person from the neutrino group at BNL maintain and update all the changes as they are developed.

The required software effort for this R&D project is 4 FTE-months during the first year to produce the proper GLoBES input for VLBNO. Thereafter, it will require about 2 FTE-month per year for maintaining the created GLoBES files including the incorporation of periodic detector updates. The GLoBES calculations are CPU-intensive because of the large number of parameters in the neutrino oscillation probabilities. The resulting computing effort at BNL could meet the increased load by using the currently existing computing resources with planned upgrades.

Proposed Work and Budget:
The projected software Task 4 R&D budget for the next three years for R&D comprises:

**R&D Task 4 – Budget by Fiscal Year**

| **Budget Item** | **FY 2006 (FY06 $K)** | **FY 2007 (FY06 $K)** | **FY 2008 (FY06 $K)** | **Sum (FY06 $K)** |
|---|---|---|---|---|
| Personnel* | 51 | 25 | 25 | 101 |
| Computing | 5 | 5 | 5 | 15 |
| Travel and Miscellaneous | 7 | 7 | 7 | 21 |
| **Totals** | **63** | **37** | **37** | **137** |

* Personnel needed: FY 2006, 07, 08, 0.3 FTE staff physicist/postdoc; FY 2007, 08, 0.15 FTE postdoc

<u>3.2 Development of Photo Sensors for Water Cerenkov and Other Detectors:</u>

Task 5 - Photo-Sensor Development for Large Detectors

<u>Task 5a</u> - Construction of a Water Cerenkov/Liquid Scintillator Detector Test Facility
A critical component in the R&D effort to improve light sensors for Water Cerenkov (WC) or Liquid Scintillator (LS) applications, is the existence of a Detector Test Facility where sensors can be tested under realistic conditions in a liquid environment. The BNL neutrino group has designed and constructed a small WC test tank to measure Cerenkov light from vertical cosmic ray muons, using a variety of sensors. Cerenkov light from the cosmic ray muons was successfully detected in the prototype tank using a PMT as the sensor. Tests using various APDs as the detection sensors are planned in the near future. The current tank was built using off-the-shelf components as a proof-of-concept and operated at room temperature. Further investment is needed to develop a larger, fully operational facility for testing various sensors and HV delivery systems in a liquid environment. In particular, the following investments are required to advance the program of photo-detector device improvements:

i)BNL has produced a conceptual design for a light-focusing mirror that will improve the light collection efficiency for Cerenkov light emitted from vertical muons (the shape and size of the prototype mirror chosen is shown in Figure 3); we need to acquire from a commercial vendor, 2-3 small prototype mirrors at an estimated cost of $20,000/each;

ii)In addition, we would like to start R&D on manufacturing mirrors at low cost at high volume. These mirrors should be able to withstand immersion in pure water for several decades. To our knowledge only the SNO collaboration has done such R&D in the past, but for relatively small mirrors. Our collaborators (Mel Ulmer and his group) at Northwestern University would like perform such R&D using their existing

facilities. They require some funding for carrying this work out: support for 1 postdoc and student for 1 year and money for materials and manufacturing.
iii) we need to acquire a commercial water filtration and purification system of appropriate capacity;
iv) we need funding support for the mechanical design and construction of a large water tank for measuring the response of larger area and multiple sensor arrays.

We estimate staffing needs of 1.0 FTE postdoctoral physicist + 0.5 FTE of a mechanical technician, for each of two fiscal years, FY 2006 and 2007, will be needed for design and construction of the WC test tank, for mounting the focusing mirror, and for implementing the water filtration and purification system. Operation of the test facility in FY 2008 will require 1.0 FTE postdoc + 0.25 FTE mechanical technician.

In very large WC and LS detectors, PMTs and hybrid vacuum tube technologies are subject to large pressures across their surface. For example, in a WC detector the size of UNO, photo-sensors at the bottom of a 60m column of water experience a pressure of 85psi. Photo-sensors based on vacuum tube technologies need extensive testing under pressure to decide their feasibility for use in a mega-ton detector. In addition to a liquid test facility, the BNL neutrino group plans to design and build a test setup to assess the mechanical robustness and hardiness of hybrid photo-sensors under pressure. In FY 2008, 1.0 FTE of detector physicist/engineer plus 0.25 FTE mechanical technician will be needed to design and construct the pressure testing capability just described.

Task 5b - Development of Hybrid Photo Diode (HPD) technologies, development of optics for large scale imaging readout, testing of solid state light sensor technology in water Cerenkov environment.

The BNL neutrino group plans to acquire a 61 pixel HPD from DEP and to begin evaluating this device with low noise electronics manufactured by Integrated Detector and Electronics AS, Norway and currently used by Weilhammer's lab at CERN. The aim is to develop an electronic readout appropriate for long baseline neutrino event rates. In conjunction with the optics simulations we will begin also to explore novel designs for the electrostatic focus of produced photo-electrons in a PMT that has been optimized for our application.

The BNL group would also like to acquire HPDs with APD readout such as the Hammamatsu hybrid PMTs shown in Figure 5. In addition we would like to obtain or commission the manufacturing of HPDs with multi-pixel APD readout.

To evaluate the use of these devices properly we will need to perform optics simulations using commercial optics software such as ZEMAX. We have aquired this software, but need a dedicated person to run the simulations and optimize the design for a large imaging detector.

The estimated personnel need for this task is 0.5 FTE of a detector physicist/electronics engineer, coupled with 0.25 FTE of electronic technician effort for each of the first two years, FY 2006, 2007. This staffing will be shared with an equal effort for Task 5a utilizing the same individuals.
In conjuction with above R&D on hybrid PMTs, we would like to continue testing and evaluation of solid state sensors such as APDs. Since hybrid PMT technology will very likely include solid state sensors for detecting the emitted electrons, we would also like to study them separately to understand the challenges to the electronics. The BNL neutrino group would like to acquire more large area APDs from several companies for performance characterization and comparison. For example, APDs manufactured by Hamamtsu as well as more APDs from RMD.

We would like to continue pursuing APD R&D efforts in partnership with industry to improve the manufacturing process of large area, high-gain APDs. We propose to encourage and promote:

i) improvement of electrical properties and quality control in the APD manufacturing process, especially for large-area and high-gain APDs that are still in the prototyping stage; the manufacture of larger numbers of prototype APDs is needed to be able to assess response uniformity;
ii) continue the development of waterproof packaging, plus a high-voltage (HV) delivery system to allow APDs to be immersed in water or liquid scintillator;

Given that APDs have significantly lower gain than PMTs, the coupling of high-gain APDs with low-noise charge amplification electronics is critical to enabling good time resolution measurements with a good signal to noise ratio. Different photo-sensors have different gain, input capacitance and series resistance. Therefore, we would like to develop in-house, custom-made electronic readout that is best matched to the electrical properties of the APDs under test. This effort necessitates assembling an in-house Laboratory technical support effort dedicated to the design and manufacturing of custom-made low-noise charge amplifiers and a HV delivery system. The estimated personnel need for this task is 0.5 FTE of a detector physicist/electronics engineer, coupled with 0.25 FTE of electronic technician effort for each of the first two years, FY 2006, 2007. This staffing will be shared with an equal effort for Task 5b utilizing the same individuals.

Proposed Work and Budget:
The projected Tasks 5a, 5b R&D budgets for the next three years comprise:

**R&D Tasks 5a, 5b and 5c – Budget by Fiscal Year**

| Budget Item | FY 2006 (FY06 $K) | FY 2007 (FY06 $K) | FY 2008 (FY06 $K) | Sum (FY06 $K) |
|---|---|---|---|---|
| Personnel* | 417 | 417 | 345 | 1179 |
| R&D Test Items/Eqp. | 150 | 100 | 50 | 300 |
| Travel and Miscellaneous | 7 | 7 | 7 | 21 |
| **Totals** | **574** | **524** | **402** | **1500** |

* Personnel needed: FY 2006-08, 1.0 FTE detector physicist/engineer + 1.0 FTE postdoc each year; also, electronic/mechanical technician effort at the summed levels of 1.0, 1.0 and 0.5 FTE in each of FY 2006, 07, 08, respectively.

## 3.3 Liquid Scintillator Detector R&D:

The projects discussed in Section 2.3 are detailed in the proposed R&D tasks described in the following sections.

### 3.3.1 Liquid Scintillator Detector R&D

The importance of reactor-based experiments for the next stage of neutrino oscillations research has been well recognized in the neutrino research community. To optimize the capabilities of the associated experimental detectors, R&D is needed for new liquid scintillator (LS) materials. Such new scintillators could also have applications for very large neutrino detectors at a later stage of neutrino research. The R&D proposed here is centered in the BNL Chemistry Department's Solar-Neutrino/Nuclear-Chemistry Group. The two main efforts currently going on in the Group are discussed below in Tasks 6 and 7

Task 6 - Gd-Loaded Liquid Scintillator for Reactor Experiments

The Solar-Neutrino/Nuclear-Chemistry Group ("the Nuclear-Chemistry Group") is a participant in two existing U.S.-based $\theta_{13}$ R&D projects: (a) the Braidwood experiment (co-spokesmen Michael Shaevitz of Columbia U. and Edward Blucher of U. Chicago) that would be done at the Braidwood reactor in Illinois, which is run by the Exelon Co.; and (b) the Daya Bay experiment (co-spokesmen Stuart Freedman of UC-

Berkeley and LBNL and Yifang Wang of IHEP, Beijing) that would be done at the Daya Bay nuclear-reactor power-station near Shenzhen, China, an hour's drive north of Hong Kong.

Both collaborations (with the participation of the Nuclear-Chemistry Group) have been active for the last 1-2 years. In fact, in the fall of 2004, the Braidwood collaboration[31] submitted identical *proposals for R&D funding to NSF and DOE*; at that time, the Daya Bay collaboration[32] made a *brief R&D submission to NSF*; recently it prepared a lengthy document to send to both *NSF and DOE*. The purpose of these proposals is to obtain funding on the order of $1 M each for continued R&D and for detailed engineering studies in preparation for full-scale construction proposals that will be submitted in 2006.

**Gd-loaded Liquid Scintillator Performance**

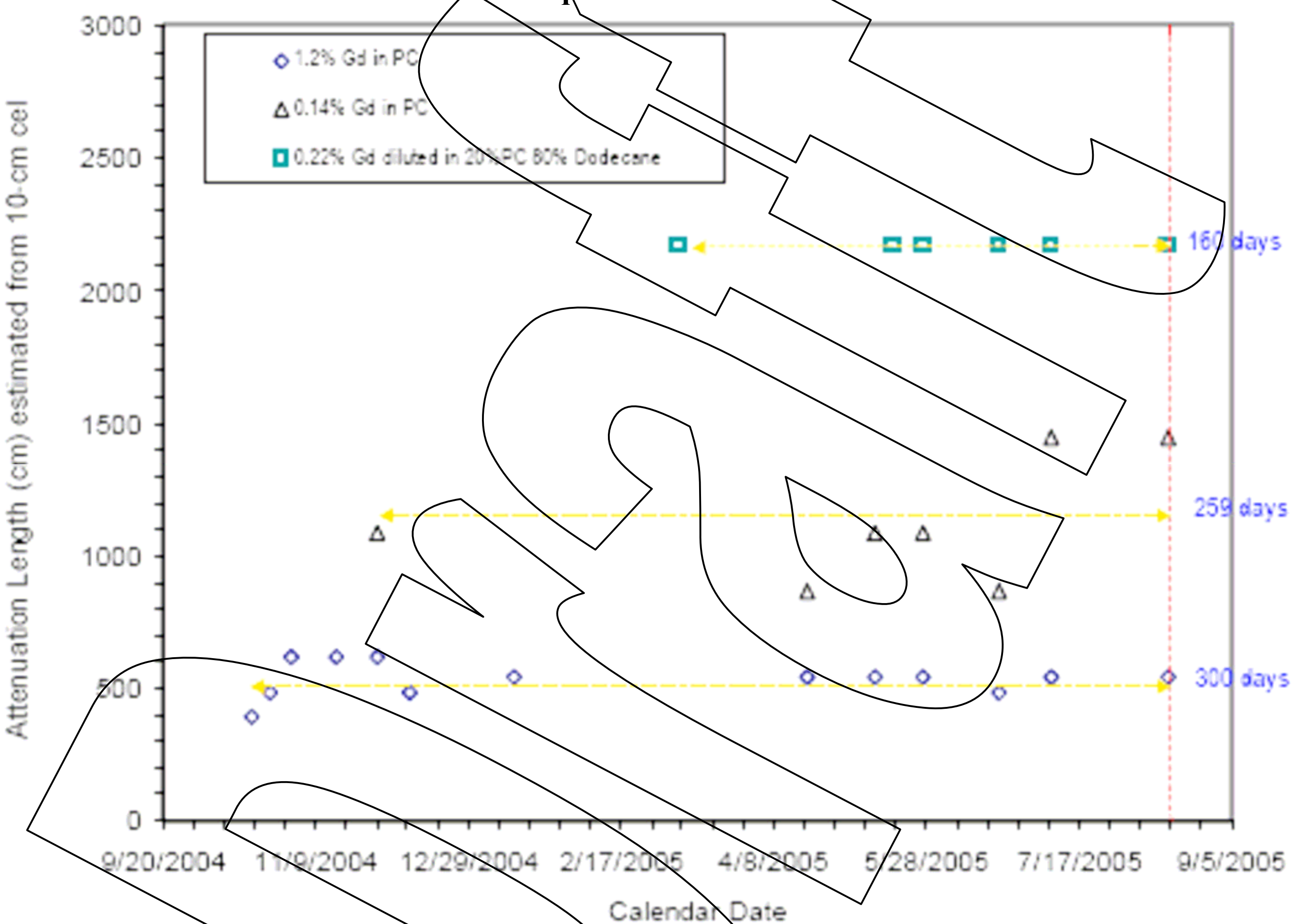



*Figure 10. Stability over time of Gd-loaded liquid scintillator*

The role of the Nuclear-Chemistry Group is the same in both collaborations: to develop and perfect chemical procedures for the synthesis of the gadolinium-loaded organic liquid scintillator ("Gd-LS", with Gd concentrations ~0.1-0.2% by weight). The Gd is a critical functional element of the antineutrino detector, to detect the delayed signal from the neutrons that are produced by capture of the antineutrinos on hydrogen (protons) in the LS. Because of its huge cross section for (n,γ) capture, 49000 barns, Gd has been used for many years to detect neutrons from nuclear reactors. But the application of Gd-LS to antineutrino experiments requires stringent constraints on the properties of the Gd-LS. Those that have been identified by the BNL Group as key indicators of excellent Gd-LS performance in $\theta_{13}$ experiments are: extreme long-term chemical stability (for an operating period of the antineutrino detector of more than 3 years); high light output; and high optical transparency (i.e., the optical attenuation length A. L. ≥ 10 meters).

Other important issues that the Group has begun to study include the chemical compatibility of the Gd-LS with the detector vessel (which will likely be made of a plastic such as acrylic or nylon), and the assay, removal and control in the Gd-LS of the chemical and the radioactive impurities from the naturally occurring uranium and thorium decay chains. Some notable achievements that the Group has obtained to date, mainly with pseudocumene (PC) as the organic LS medium (and more recently with a mixture of PC and dodecane), are the preparation of samples of Gd-LS with: (1) excellent optical transparencies, with A. L. ~15 meters; (2) light output ~95% of pure PC; and (3) perhaps most importantly, stability of these crucial properties over a period to date of ~300 days. Fig. 10 illustrates these achievements; the attenuation length (AL) for several of the Gd-LS formulations are stable over the time periods elapsed since the chemical preparation of each Gd-LS sample.

The proposals that were made to the funding agencies by the two collaborations included some requested funding for the BNL Nuclear-Chemistry Group for chemical supplies and equipment, ~$40 K. However, there were no specific requests in these proposals by any of the participating institutions for additional scientists to do the R&D. The BNL Group is small at present, with two staff members, one postdoc, and one part-time chemical consultant. To perform all of the designated tasks that need to be done in the next year or so, including preparing hundreds of liters of Gd-LS for collaboration colleagues to test in prototype antineutrino detector modules, the Group will have to hire at least two more postdocs or junior scientists for a minimum of two years. To start this process, Hahn *has already requested and received BNL LDRD funding at ~$150 K per year, to begin in FY 2006.* These funds will support one postdoc and pay for needed materials and equipment for large-scale preparations of Gd-LS.

If one or both $\theta_{13}$ construction projects receive U.S. funding, the experiments will utilize four or more identical antineutrino detectors, each one containing 65 tons or more of Gd-LS. Construction would begin in ~2007, with data taking projected to begin in 2009 or 2010. To meet this ambitious schedule, the BNL Nuclear-Chemistry Group will certainly have to grow to at least double its current size in order to coordinate and/or perform the required industrial-scale production of the Gd-LS, following the chemical recipes that the Group has/will have developed. If the production can be done by the chemical industry, the BNL Group will have to develop the detailed acceptance specifications and do the Quality Control of the product Gd-LS. Or if it turns out that a high-quality product cannot be made by industry, it is conceivable that new chemical facilities will have to be built at BNL.

Two special notes:

(1) The BNL Solar-Neutrino/Nuclear-Chemistry Group has traditionally received research funding from DOE's Office of Nuclear Physics (ONP) for its participation in two solar-neutrino experiments, GALLEX at the Gran Sasso Laboratory in Italy, and the Sudbury Neutrino Observatory, SNO, in Canada. However, there has been some speculation that, instead of following the "KamLAND" model where both ONP and Office of High Energy Physics (OHEP) shared in providing the U.S. part of the funding, a new model may be developed where ONP will focus on funding new double beta-decay experiments and OHEP will focus on funding the reactor $\theta_{13}$ experiments. In that case, it will be especially important that the BNL group's work be included in the present BNL Neutrino Proposal to OHEP.

(2) The BNL Physics Department has entered into discussions with the Theta-13 collaborations with the intention of joining the reactor neutrino efforts. The physicists in the department see the time frame for the reactor experiments as complementary to the longer time frame for the VLBNO experiments.

Proposed Work and Budget:
The projected LS R&D budgets for the next three years for R&D Task-6 comprise:

**R&D Task 6 - Budget by Fiscal Year**

| Budget Item | FY 2006 (FY06 $K) | FY 2007 (FY06 $K) | FY 2008 (FY06 $K) | Sum (FY06 $K) |
|---|---|---|---|---|
| Personnel [a] | 160 | 160 | 500 | 820 |
| Eqp. and Chemicals [b] | 100 | 80 | 40 | 220 |
| **Totals** | **260** | **240** | **540** | **1040** |

[a] Personnel needed in addition to those who will be supported by the BNL LDRD: FY 2006 and 2007, 2 postdocs; FY 2008, 2 staff physicists + 2 postdocs

[b] By FY 2008, construction should have started on the $\theta_{13}$ experiments, so that requirements for chemicals and equipment will be reduced for R&D

Task 7 - Fine-Grained Liquid Scintillator Detector Development

Prototype Calorimeter - The proposed R&D project would construct a prototype detector with a $(50cm)^3$ liquid scintillator volume ($0.125\ m^3$ or 125 liters) interleaved with a grid of wavelength-shifting fibers to detect the light from neutrino and neutron interaction products. This detector concept was developed for the FINeSSE experiment[33] to measure neutrino reactions in a ~10 ton detector at a near (~100m) location with an intense neutrino source. A mid-sized prototype would allow us to demonstrate the tracking and reconstruction capability of this detector technique.

In addition to demonstrating the viability of this neutrino detector technology, a prototype would allow us to investigate various liquid scintillators with additives such as gadolinium (Gd) or lithium (Li). These elements are noted for high neutron detection efficiency and, as noted above, the Gd-LS will be used in the planned antineutrino experiment to measure $\theta_{13}$. A fine-grained detector would enable a measurement of the neutron capture efficiency on Gd.

This program would also allow for the investigation of alternatives to standard carbon-based organic- liquid scintillator. These have the drawbacks of expense, and, for several organic LS, relatively low flash point. Megaton-scale underground detectors are likely to be water-based. A water-based liquid scintillator could be used in a tracking detector such as this to precisely measure neutrino reaction rates on oxygen and be directly applicable for large long-baseline neutrino oscillation studies.

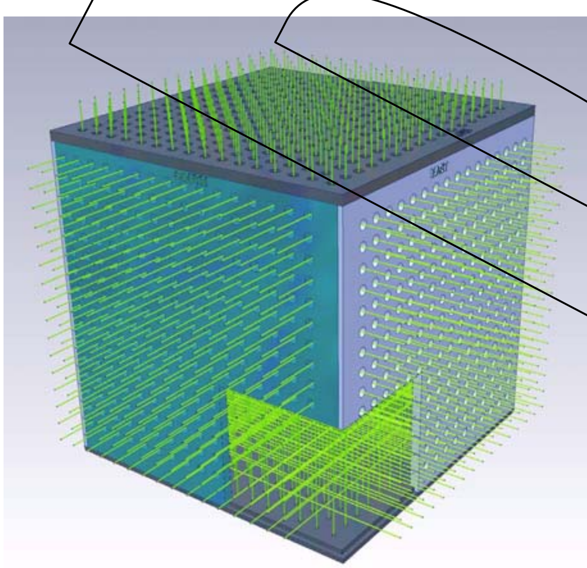


*Figure 11. A schematic diagram of the proposed detector*

The proposed detector, shown in Figure 11, consists of a cubic container, 50 cm on a side (125 liter volume). Between each pair of opposite sides there is an array of 16 by 16 (768) wavelength-shifting (WLS) fibers (a total of). The fibers have a diameter of 1.5 mm and are 2.5 cm apart. The ends of the WLS fibers outside the container are coupled to clear optical fibers that in turn are aligned with the pixels of an 8 by 8 channel, Hamamatsu R7600-00-M64 multi-anode photomultiplier (MAPMT). In addition, an optically-separated veto region will surround the inner volume in order to tag entering or exiting particles. This region will be also be read out with a (sparse) WLS fiber array.

The readout electronics are being developed at the Indiana University Cyclotron Facility (IUCF), based on a scheme that is in use for the STAR end cap detector at RHIC. The signal from each MAPMT channel is sampled continuously at a 10 MHz rate by a 12-bit ADC. After a pulse is encountered, the sample information is converted to a pulse amplitude and time (with a resolution of $\pm$ 0.1 ns) by an on-board CPU. The board also contains the high voltage supplies for the photomultipliers. Eight such boards are packaged together to read out one entire MAPMT and are powered by a 48V (12W) power supply. The data are sent to the data acquisition computer via Ethernet (or equivalent) for further analysis.

This detector concept was developed for the FINeSSE experiment to measure neutrino-nucleon neutral-current elastic scattering and was motivated by the desire to precisely reconstruct 100-1000 MeV proton tracks in a large-volume neutrino detector. A prototype of this size will allow us to measure several physics processes while demonstrating the viability of the design with an intermediate-sized detector. The concept was shown to work with a small (15cm x 15cm x 30cm) prototype detector and Monte Carlo simulations of a large (2.5 x 2.5 x 2.5m$^3$) detector[12]. An intermediate detector will allow us to demonstrate:

- tracking of protons and muons in three dimensions,
- neutron identification via its delayed capture signature,
- viability of the on-board electronics scheme, and
- the construction of this intricate detector on a large scale.

[33] *L. Bugel et al., arXiv:hep-ex/0402007*

Liquid Scintillator R&D - The large volume (125 liters) and fine granularity of this prototype detector will allow for detailed investigations of the nuclear and chemical processes involved with neutrino detection in liquid scintillator. In particular, three types of liquid scintillator will be investigated: Gd-loaded, Li-loaded, and water-based.

*Gd-loaded liquid scintillator*

The proposed Braidwood and Daya Bay reactor neutrino experiments are considering the use of Gd-loaded liquid scintillator. As noted, the BNL Nuclear-Chemistry group is doing the R&D for this scintillator. In addition to the design and prototype studies going on in the Braidwood and the Daya Bay collaborations. this fine granularity detector prototype by IUCF could be used to better understand the response of this scintillator to the neutrons produced in the reactor antineutrino interactions. In particular, the Gd/H neutron capture fraction could be measured with an Am-Be tagged neutron source immersed in the detector.

For this measurement the detector would be filled with Gd-loaded liquid scintillator of the same type to be used in the proposed reactor experiments. In Gd-loaded liquid scintillator, approximately 84%[34] of neutrons capture on Gd, resulting in a cascade of photons with total energy of around 8 MeV. The remaining 16% of the neutrons capture on H resulting in a single 2.2 MeV photon. This detector is of sufficient size and has adequate energy resolution to accurately measure the Gd/H capture ratio. In addition, the excellent spatial resolution of the detector will allow for the separation of the neutron signal from any accidental signal due to cosmic rays or environmental activity.

*Li-loaded liquid scintillator*

The addition of $^6$Li to liquid scintillator would enable the detection of neutrons with high efficiency and good spatial resolution. The thermal cross section for the $^6$Li(n,$\alpha$)$^3$H is quite large and leads to a localized energy deposition of approximately 5MeV. This would allow for neutron detection with a better localization of the neutron capture location because the signature is the emission of an alpha which deposits energy in the detector at the neutron capture point. The intense ionization deposition by the alpha is likely to cause saturation of the light signal but this will not contravene the improvement in spatial localization. This is in contrast to the Gd-capture reaction that produces gammas that may travel tens of centimeters before depositing energy. The end result would be a scintillator that allows for better separation of neutrino-induced neutron production from background sources.

*Water-based liquid scintillator*
The successful development of water-based liquid scintillator would allow for an inexpensive, ecologically-friendly, safe alternative to commonly used carbon-based scintillators. In addition, it could be used in a near-detector on a long-baseline experiment to measure neutrino interaction cross sections on oxygen. These are requisite to extracting precision oscillation measurements from megaton-class water neutrino detectors. The detector technology proposed here is a good-candidate for such a near detector. It does not require a long-attenuation-length scintillator since the fiber spacing is on the order of a few cm. Scintillators that are designed to be mixed with water do exist (e.g. Inflow2:1 from IN/US Systems[35]). However, they are designed to be used in water at a relatively small water to organic component ratio, nominally 1:5 or less. The challenge is to produce a mixture with a large water to organic ratio. The BNL Nuclear Chemistry group has experience with these materials and would do the R&D to test the feasibility of producing a usable mixture that could be tested with this prototype detector.

This Task will be a collaborative effort between the neutrino group at Indiana University (IU) and the Nuclear-Chemistry Group at BNL. The prototype detector would be constructed primarily at IU within the experimental nuclear physics group at the IU Cyclotron Facility (IUCF). The liquid-scintillator R&D would take place at BNL under the direction of the Nuclear-Chemistry Group. The testing of the detector would occur using a neutron source and using test beams at IUCF or BNL.

Proposed Work and Budget:
In this Task 7, the IU group is proposing to build and test the $(50\text{cm})^3$ WLS fiber/liquid scintillator detector and use it to develop and test several types of liquid scintillator. This work would be performed in collaboration with BNL scientists in the Nuclear Chemistry Group. We are requesting funds to procure the capital equipment required to build the prototype: WLS fiber, MAPMTs, electronics, mechanical components and liquid scintillator. The group at Indiana University will supply the personnel required to build the device using other funds. We expect to procure the equipment mainly with first year funding.

**R&D Task 7 – IU Budget by Fiscal Year**

| Budget Item | FY 2006 (FY06 $K) | FY 2007 (FY06 $K) | FY 2008 (FY06 $K) | Sum (FY06 $K) |
|---|---|---|---|---|
| Personnel* | 84 | 84 | 0 | 168 |
| Materials and Supplies | 150 | 50 | 0 | 200 |
| Travel | 15 | 15 | 0 | 30 |
| **Totals** | **249** | **149** | **0** | **398** |

*Personnel needed: FY 2006 and 2007, 0.5 FTE BNL staff scientist each year.

We are also requesting assistance from the BNL Nuclear Chemistry Group to develop the optimum liquid scintillator to fill the prototype detector. The required person will be a BNL scientist with experience in liquid scintillator chemistry. The work will require 0.5 FTE per year for the BNL Group for the next two years.

Task 8 - Application of Liquid Scintillator to Large Detectors

Task 8a - LS R&D Centered at Virginia Tech University
New concepts are being developed for using Liquid Scintillator (LS) as the detection medium instead of water-Cerenkov in novel size neutrino detectors on the scale of >100 ktons. The new R&D work for such a detector below has been discussed with Prof. R. S. Raghavan of Virginia Tech University (VTU).

The VTU R&D project is proposed by a group of scientists who have contributed to the science addressed by the proposed Hyper Scintillator Detector (HSD). The proposing experimentalists are leading scientists that have made pioneering contributions to the conception, design and operation of large-scale high and low energy detectors (BOREXINO, IMB, KamLAND, MACRO and Superkamiokande ) that employ both water Cerenkov and liquid scintillation methods. A generic detector of HSD type has been under consideration for some time by members of the group from various points of interest.

Proposed Work and Budget:
Liquid scintillation technology itself is a mature technology and is used in modern massive detectors such as KamLAND and BOREXINO. The specific applications to high energy physics problems, as well as a optimization for combined high and low energy objectives, is new. We foresee four major directions that are most fruitful for further development of a very massive detector strategy:

1. Simulation work for application of scintillations to proton decay
2. Simulations of long base-line oscillations of antineutrinos.
3. Development of suitable scintillation detector media (possibly combined with Cerenkov capability)
4. Development of new detector designs of very massive detectors.

We foresee investing in 4 postdoctoral scientists to examine these 4 topics. The institutions of the working group have strong infrastructures and programs on existing large detectors so that start-up work would be relatively rapid. Thus hardware funds can be relatively a smaller fraction of the program.

The projected VTU R&D budgets for the next three years for R&D Task-8A comprise:

**R&D Task 8A– VTU Budget by Fiscal Year**

| **Budget Item** | **FY 2006 (FY06 $K)** | **FY 2007 (FY06 $K)** | **FY 2008 (FY06 $K)** | **Sum (FY06 $K)** |
|---|---|---|---|---|
| Personnel[c] | 200 | 200 | 0 | 400 |
| Hardware, Travel and Miscellaneous | 50 | 50 | 0 | 100 |
| **Totals** | **250** | **250** | **0** | **500** |

[c] Personnel needed: FY 2006 and 2007, 4 postdoctoral assistants at VTU.

Task 8b - LS R&D Centered at BNL
The BNL Nuclear Chemistry Group is well placed to contribute to such large-scale projects since, as noted earlier, it has performed R&D with liquid scintillators (LS) for the past four years, first in collaboration with Raghavan in connection with the proposed LENS low-energy solar neutrino detector and, more recently, with the $\theta_{13}$ experiments. A very important question for the BNL Nuclear Chemistry Group in all of this R&D, which has already been noted above, concerns the long-term stability of the LS, since several proposed new experiments may have lifetimes on the order of several years. It is conceivable that, in the case of organic LS that is not loaded with a metal (as used in Borexino or KamLAND), it may be possible to chemically purify the LS after the experiment has begun. However, even in that case, the purification steps will be difficult because the organic LS will contain more than one component. For example, the added fluors will behave differently during chemical purification than will the liquid components of the LS. In the case of metal-loaded LS, any chemical purification steps after the chemical synthesis has been completed will be close to impossible since most purification steps will remove the metal that had been intentionally added during the synthesis, thereby changing the properties of the LS. Furthermore, any such purification steps will be difficult to implement on the greater than kiloton scales that are being considered for the next-generation experiments.

In view of these potential problems, the BNL Nuclear Chemistry Group has paid close attention to developing purification methods that can be applied before and during the chemical preparation of the LS, e.g., to remove chemical and radioactive impurities from the LS. We also continue to develop techniques to monitor the long-term stability of our LS formulations, in what we refer to as a QC program. In particular, we have purchased and/or developed equipment to measure what we consider to be two of the key characteristics of the LS, its light output and its attenuation length (AL). For example, we have developed new systems to measure the AL of liquids: a 1-meter laser-based system (at a wavelength of 442 nm) and a new 2-meter system that we are currently building, that will use LED's to provide light at several different wavelengths, in order to measure the light transmission in the liquids as functions of pathlength and of wavelength. We are doing this work in collaboration with members of the Neutrino Group in the BNL Physics Department.

The BNL Nuclear Chemistry Group is also considering improving its capabilities for doing low-level nuclear counting, to measure the signal decay time and the photon production efficiency per unit incident energy, and to measure radioactive contaminants in the LS and in materials that are being considered as candidate construction materials for new neutrino detectors. Concomitant issues concern the chemical compatibility of the LS with the proposed materials that will comprise the detector vessel; e.g., it is well known that many organic liquids will attack various plastics, and there are standardized tests that we will use, that have been developed to test for chemical incompatibilities.

In essence, the R&D at BNL for such long-term large-scale physics applications of LS for new neutrino detectors will be in addition to our dedicated work on $\theta_{13}$ experiments. We propose to expand the Nuclear Chemistry Group on the basis of our existing, unique expertise to become a well-equipped BNL center with full capability for the preparation, purification, and systematic monitoring and analysis of new LS materials. This expansion will be phased in gradually in FY 2007 and 2008, by which time the funding decisions and planning schedules will have been implemented for the reactor $\theta_{13}$ experiments[31, 32]. This long-range plan may well be advantageous for future double-beta nuclear decay (such as the proposed SNO-PLUS experiment at SNOLAB in Sudbury) and the long baseline neutrino experiments.

The projected BNL R&D budgets for the next three years for R&D Task-8B comprise:

**Task 8B – BNL R&D Budget by Fiscal Year**

| Budget Item | FY 2006 (FY06 $K) | FY 2007 (FY06 $K) | FY 2008 (FY06 $K) | Sum (FY06 $K) |
|---|---|---|---|---|
| Personnel[d] | 0 | 80 | 360 | 440 |
| Eqp. And Chemicals | 0 | 60 | **60** | 120 |
| **Totals** | **0** | **140** | **420** | **560** |

[d] Personnel needed: FY 2007, 1 postdoc; FY 2008, 1 staff physicists + 2 postdocs

3.4 Liquid Argon Large Detector R&D

Task 9 – Application of Liquid Argon to Large Detectors

The work to be accomplished in this task consists of physics analysis intended to verify that a 100 kT LAr detector, exploiting all (or most) of the charged-current channels, can produce the same physics reach as a 500 kT water Cerenkov detector using only the quasi-elastic channel, as well as software creation and simulation activities to establish credible efficiencies for $\nu_e$ and $\pi^0$ background rejection in a LAr detector of this scale. It will also be important to verify that a LAr detector can operate with acceptable live-time for neutrino-beam based oscillation physics in the surface (or near-surface) cosmic ray background (ignoring proton decay). This work will involve staff physicist and postdoc effort over the next two years and will require that new software be created to simulate a 100 kT LAr drift detector, the behavior of neutrino signal events and cosmic ray background events in this detector and to demonstrate the hypothesized properties of such a new detector for neutrino oscillation physics.

A second important task is to establish a realistic cost estimate for a 100 kT LAr detector, based on current or reasonably achievable (conservative) technology. This work will involve collaboration between physicists with mechanical, cryogenic and electronics engineers to produce a credible conceptual design for the detector and its support systems and create a preliminary cost estimate for this design. Task 9 does not envision pursuing the geo-technical engineering effort to produce a conceptual design for excavating and stabilizing the large, deep underground cavern to house the LAr detector. However, this task will produce a conceptual design for operating the cryogenic and air safety technical support systems in the cavern. This work will be carried out in collaboration with university physicists from Yale, Princeton and UCLA .

Proposed Work and Budget:
The projected software Task 9 R&D budget for the next three years for R&D comprises:

**R&D Task 9 – Budget by Fiscal Year**

| **Budget Item** | **FY 2006 (FY06 $K)** | **FY 2007 (FY06 $K)** | **FY 2008 (FY06 $K)** | **Sum (FY06 $K)** |
|---|---|---|---|---|
| Personnel* | 190 | 190 | 190 | 570 |
| Travel and Miscellaneous | 10 | 10 | 10 | 30 |
| **Totals** | **200** | **200** | **200** | **600** |

- Personnel needed: FY 2006, 07, 08, 1 FTE postdoc; FY 2006, 07, 08, 1 FTE engineer

**References**

[1] “The Physics of the Universe, a Strategic Plan for Federal Research at the Intersection of Physics and Astronomy ”, National Science and Technology Council Committee on Science, February 2004, http://www.ostp.gov/html/physicsoftheuniverse2.pdf ; also, “FY 2007 Administration Research and Development Budget Priorities”, J.H. Marburger, III and J.B. Bolten, Executive Office of the President Memorandum, July 8, 2005, http://www.ostp.gov/html/budget/2007/ostp_omb_guidancememo_FY07.pdf

[2] DUSEL news, http://www.nsf.gov/news/news_summ.jsp?cntn_id=104313&org=MPS&from=news

[3] “Neutrinos and Beyond – New Windows on Nature”, National Research Council Study, National Academies Press, 2003.

[4] M. Diwan et al., Phys. Rev. D. 68, 012002 (2003).

[5] M. Diwan, "The Case for a Super Neutrino Beam", Proceedings of the Heavy Quarks and Leptons Workshop 2004, San Juan, Puerto Rico, 1-5 June (2004). hep-ex/0407047.

[6] W. Marciano, “Extra Long Baseline Neutrino Oscillations and CP Violation”, arXiv:hep-ph/0108181 v1, 2001.

[7] A. Strumia & F. Vissani, hep-ph/0503246 IFUP-TH-2005-06, Mar 2005.

[8] UNO EOI, http://nngroup.physics.sunysb.edu/uno/publications.shtml

[9] LAr Detector homepage, http://www.aquila.infn.it/icarus/exp.html

[10] Super Kamiokand detector homepage, http://www-sk.icrr.u-tokyo.ac.jp/sk/index_e.html

[11] SNO detector homepage, http://www.sno.phy.queensu.ca/

[12] C.B. Bratton et al., Phys. Rev. **D 37,** 3361 (1988); K. Hirata et al., Phys. Rev. **D 38**, 448 (1988)

[13] M.L. Constantini and F. Vissani, e-Print Archive: astro-ph/0508152

[14] T. Araki et al., Nature Vol. 436 No. 7050, p. 499 (2005).

[15] C. Yanagisawa, Stony Brook University. Presentation at NNN05, NuFACT05; http://nnn05.in2p3.fr/trans/yanagisawa.ppt

[16] P. Huber, M. Lindner and W. Winter, “Simulation of long-baseline neutrino oscillation experiments with GLoBES, Phys. Commun. **167**, 195 (2005); arXiv hep-ph/0407333; HEP-PH 0407333.

[17] Kobayashi UNO05 water clarity reference

[18] Presentations at NNN05; http://nnn05.in2p3.fr/schedule.html

[19] Shiozawa NNN05 reference

[20] Esso Flyckt, Photonis, Nufact05

[21] P. Atonioli et al. Nuc. Instr. and Meth. **A433** (1999) 104.

[22] KAMLAND web page; http://www.awa.tohoku.ac.jp/html/kamLAND

[23] C. Rubbia, "The Liquid-Argon Time Projection Chamber: A New Concept For Neutrino Detector", CERN-EP/77-08 (1977).

[24] ICARUS Collaboration, "Design, construction and tests of the ICARUS T600 detector", Nucl. Instr. and Meth. A527, 329 (2004).

[25] D.B. Cline et all., LANNDD, “A Large Magnetized Liquid Argon Detector for Proton Decay, Neutrino Factory and Solar Neutrino” (Jan 16, 2001), http://www.hep.princeton.edu/mcdonald/nufact/neutrinotrans6.pdf

[26] D.B. Cline et al., LANNDD, "A Massive Liquid Argon Detector for Proton Decay, Supernova and Solar Neutrino Studies, and a Neutrino Factory Detector" (May, 2001), astro-ph/0105442, Nucl. Instr. and Meth. A503, 136 (2003).

[27] F. Sergiampietri, "On the Possibility to Extrapolate Liquid Argon Technology to a Supermassive Detector for a Future Neutrino Factory", presented at NuFACT'01 (May 26, 2001), http://www.hep.princeton.edu/~mcdonald/nufact/nufact01.pdf

[28] G.T. Mulholland, LANNDD Feasibility Study, (Aug. 13, 2002), http://www.hep.princeton.edu/~mcdonald/nufact/mulholland/ELANProposal.pdf

[29] D.B. Cline et al., "Proposal to Study the Feasibility to Site Various Neutrino Detectors at WIPP for Neutrino Factories or Superbeams", (Apr. 17, 2002), http://www.hep.princeton.edu/~mcdonald/nufact/April17-WIPPproposal.pdf

[30] Finley et al., "A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam", Fermilab FN-0776-E (Sept.21, 2005), http://www-lartpc.hep.fnal.gov/tex-les/LArTPC.pdf
[31] Braidwood Neutrino Experiment homepage, http://braidwood.uchicago.edu/
[32] Daya Bay Neutrino Experiment homepage, http://bes.ihep.ac.cn/dayawane/
[33] L. Bugel et al., arXiv:hep-ex/0402007.
[34] Gd-loaded Scintillator Reference, talk presented at Erice School by R. Hahn, http://www.uni-tuebingen.de/erice/2005/sec/talks/Hahn%20-%20Erice%202005.ppt

[35] Water Scintillators Reference, http://www.inus.com/docs/inflow.htm